A FRAMEWORK FOR IMPLEMENTING SURFACE WATER TREATMENT TRAINS FOR LARGE DEVELOPMENTS

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ABSTRACT

Urban growth and the associated urbanisation has led to increased pressure on the natural environment. Associated with climate change, the development of large urban and industrial areas has been found to be responsible for water quality degradation and recent flooding of watercourses. In parallel, increased pressure on land and costs associated with developments tend to place pressure on the space allocated to amenity in cities. This is despite the fact that amenity has been found to act positively on residents in terms of their wellbeing by raising living standards.

Within this context, urban drainage has a key role to play by providing water quality, water quantity and amenity benefits according to the SuDS triangle philosophy. However, it is felt that urban drainage could potentially offer more than its current benefits by implementing SuDS in series; a treatment train. Indeed, despite environmental regulator guidance (CIRIA, 2007) a significant proportion of sites in Scotland are developed with a single "end-of-pipe" pond.

Within this context, the research undertaken aimed to develop a framework which may be used by an environmental regulator to implement treatment trains and maximise potential water quality, water quantity and amenity benefits while preventing excessive constraints for other stakeholders involved in SuDS implementation. In this regard, the fears and expectations of stakeholders are investigated using structured interviews and questionnaires. This step allowed underlining drivers and barriers to SuDS implementation to be identified and a set of quantitative benchmarks to be developed including cost of construction and maintenance, land take, pollutant removal, attenuation volume and the willingness to pay for amenity benefits.

To determine how the benchmarks interrelated, two case studies were investigated in Scotland: The Dalmarnock Road Area in Glasgow and the Houston Industrial Estate in Livingston. Based on water quality modelling using MUSIC and hydraulic modelling using Infoworks CS, it has been shown that the benefits, in terms of water treatment and attenuation, should be seen in the context of increased land take and/or costs for the area considered for virtually all the SUDS techniques.

Based on the conclusions of the investigations, a general framework was formulated to optimise SuDS treatment trains for large developments. The framework, based on iterative water quality and hydraulic modelling aims to identify the relationship between drivers and barriers to SuDS implementation. The final decision regarding the extent to which the treatment train can be implemented can then be taken knowing its implications for all the stakeholders.

To my wife, Delphine

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GLOSSARY

CBP	Concrete Block Pavement
CIRIA	Construction Industry Research and Information Association
CSO	Combined Systems Overflows
EA	Environment Agency
IT	Infiltration Trench
LW	Linear Wetland
MCDM	Multi Criteria Decision making
SEPA	Scottish Environmental Protection Agency
SIMD	Scottish Index of Multiple Deprivations
SO	Soak away
SS	Sub-surface Storage
SuDS	Sustainable Drainage System
SW	Swales
WB	Water Butt
WTP	Willingness to Pay
WWTP	Waste Water Treatment Plant

PUBLICATIONS

Journal publications

Bastien N., Arthur S., and McLaughlin M. (2010). "Valuing Amenity - Public perceptions of SuDS ponds in Scotland." Water and Environment Journal (26): 19-29.

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Chapter 1 - INTRODUCTION

1.1 BACKGROUND

The United Kingdom has recently suffered from numerous flooding incidents which resulted in damage to property, disruption and loss of human life (Cashman, 2007). In parallel to this there has been a rising degradation of the water bodies, with over 36% being observed in Scotland as having moderate to bad water quality (SEPA, 2009; Ferrier et al., 2001). Urban drainage systems, combined with the effects of climate change (Lu et al., 2001), are responsible for a great part of these degradations (Marsden and Mackay, 2001; Walker et al., 1999). This situation has raised wider concerns regarding the ability of drainage systems to adequately drain rainwater whist also protecting the environment (Hatt et al., 2004; Hollis, 1975).

Historically, drainage systems were built as combined systems where surface runoff and foul water are drained together to waste water treatment plants (WWTP). This system includes combined sewer overflows (CSOs) to provide relief during rainfall events when excess flow is discharged to a nearby river. Despite improvements in CSO design, the extension of drainage systems associated with urban growth and climate change effects tend to exacerbate the issue. Although most of the new UK drainage systems remain combined after 1945, separate pipe networks are constructed (Harremoes, 2002; Butler and Davies, 2009) in response to intermittent CSO discharges. In separate systems, surface water and foul water are drained in separate pipes, with foul water being treated by the waste water treatment plant, whilst rainwater is drained to the natural environment without prior treatment. However, the development of impermeable surfaces and the pollution generated by urban, industrial and agricultural land uses leads to the discharge of un-attenuated and polluted surface water to receiving watercourses. The discharge of surface water, untreated and un-attenuated was soon found to be responsible for the degradation of the receiving water bodies as well as contributing significantly to flood risk. To manage this, the use of Sustainable Drainage Systems (SuDS) became compulsory for virtually every new development built after April 2007 in Scotland. SuDS, using a wide range of techniques, aim to treat and attenuate surface water before discharging into receiving water-bodies as well as providing amenity and biodiversity in cities. However, despite recent legislation and guidance, the full implementation of SuDS is still relatively limited.

In parallel to the evolution of urban drainage systems since 1945, excessive urban growth has considerably reduced the opportunity for residents to access open and green spaces in many towns and cities. Rising land values at the heart of a culture which aims to maximise return on investment has left insufficient thought to the development of amenity spaces. This is despite the positive impact amenity spaces have on well-being (Greenspace Scotland, 2008). Combined with the effects of climate change and polluted runoff from urban surfaces (Lu et al., 2001), the loss of green space in cites also led to a drastic reduction in the available biodiversity in the natural environment (Mackey and Mudge, 2010). To mitigate this, SuDS, by providing water quality treatment and attenuation to the runoff discharged to watercourses have the potential to reduce anthropogenic impact on the natural environment. In addition, SuDS can also be an integral part of the city and provide amenity to the surroundings as well as, potentially, provide support for enhanced biodiversity.

Within this context, the wider use of SuDS provides an opportunity to address water quality degradation in water bodies, flood risk and the loss of green spaces and biodiversity in cities in response to the challenges of urban growth and climate change. However, to do this the different drainage systems types inherited from developments since 1850, the contrasting land uses and site characteristics need to be addressed differently.

1.2 RESEARCH AND OBJECTIVES

The overall aim of the research presented in this thesis is to optimise the implementation of SuDS controls to complement separate systems and in particular, the use of SuDS in series (“a treatment train”). Indeed, while the potential benefits of using SuDS in series have been acknowledged, the use of single SuDS, “end-of-pipe” SuDS, allowing treating and attenuating runoff is still the most common form of implementation in Scotland. Considering current expectations in terms of water quality, biodiversity and flood defences required by European, national or even local policies, a move from current drainage practice is necessary. The objective of the presented research is therefore to provide decision makers involved in SuDS implementation with a framework within which the selection of the best treatment train strategy is possible in a manner which takes into account the impact of SuDS on the stakeholders involved in their implementation. This aim is achieved by meeting the following objectives:

- To identify the opportunities and challenges stakeholders associate with SuDS implementation;
- To propose a set of quantitative benchmarks representative of stakeholder fears and expectations identified at the first stage.
- To establish the values of the quantiative benchmarks through application to cases studies and via a series of targeted interviews supported by a structured questionnaire.
- To propose a framework, based on the results of the investigation, for the selection of the best SuDS strategy to adopt based on development characteristics.

1.3 THESIS OUTLINE

The sections below highlight the different chapters developed in this thesis and the research undertaken to answer the research question established in Section 1.2.

Chapter 2 - : Literature review

This chapter present the literature review relevant to the research project. The literature review focuses on the issues resulting from urbanisation and the techniques that can be used to offset the adverse effects of urbanisation on surface water. The review of the different SUDS techniques and the associated philosophy regarding their implementation associated with key Scottish projects underline that SuDS implementation is key to the protection of water quality and management of flood risk. However, current implementation, with regards to the different stakeholders, underlines the difficulty in implementing SuDS philosophy for every development, new or existing.

Chapter 3 - : Methodology

This chapter aims at establishing a methodology to compare effectively competing SuDS treatment trains. Based on semi-structured interviews and relevant literature, the research identifies drivers and barriers for the implementation of SuDS devices. Identification of the barriers and the drivers lead to the establishment of quantitative benchmarks.

Chapter 4 - : Valuing Amenity - Public perceptions of SuDS ponds in Scotland

While primary drivers for SuDS implementation have been identified through interviews with key stakeholders, the role played by SuDS in the urban environment for residents needed to be clarified. In order to understand the potential drivers for SuDS implementation, structured interviews of residents living nearby existing SuDS projects has been undertaken. The result of the survey leads to identify residents as key stakeholders with a key interest in SuDS biodiversity. These stakeholders can potentially have a significant monetary input in the project under certain conditions.

Chapter 5 - : Feasibility studies: Dalmarnock Road Area and Houston Industrial area

This chapter investigates the feasibility to implement SuDS for different areas. The chapter looks at three different case studies with different site, catchment and land use characteristics. The chapter is based on the philosophy that the benefits, in terms of water treatment and attenuation, should be seen in the context of increased land take and/or costs for the area considered for virtually all the SUDS techniques. The different site, land use and catchment characteristics of the three cases studies considered highlight that objectives to fulfil is overwhelmingly site specific.

Chapter 6 - : Framework

This chapter establishes a framework that can be used by stakeholders to make a decision based on knowledge of the opportunities and challenges presented by the implementation of SuDS. The developed framework is applied to the three case studies investigated in Chapter 5 and allows the selection of the best SuDS solution.

Chapter 7 - : Conclusions and discussion

The chapter, as well as discussing limitation of the presented framework, draws the general conclusions outputs of the research and offers potential further research opportunities that need to be done to strengthen the proposed methodology.

Chapter 2 - LITERATURE REVIEW

Urbanisation and industrialisation have led to drastic increases in the amount of impermeable surfaces in many river catchments. In addition to the impacts of climate change, uncontrolled development can impact on water and land resources by modifying the water cycle. Runoff and wash-off from these surfaces increase both diffuse pollution and flood risk. Within this context, the protection of water bodies from pollution and managing flood risk is key to protecting resources and achieving sustainable development, defined as a way of living without affecting the need of future generations (UN, 1987).

Understanding the consequences of urbanization and industrialization on the environment is key to understanding how SuDS can help mitigate the adverse impacts of developments. This chapter reviews the potential impacts of urban and industrial activities and how these impact on the water cycle (Section 2.1), the SuDS techniques that could potentially be used to mitigate these impacts (Section 2.2), current guidance practice in Scotland (Section 2.3) and existing supporting tools to facilitate design and implementation (Section 2.5).

2.1 IMPACT OF URBANIZATION ON URBAN RUNOFF AND RECEIVING WATER BODIES

The degradation of natural water bodies has been reported in several studies. The monitoring of key water quality parameters has shown that water carries a wide range of pollutants such as suspended solids, heavy metals, polycyclic aromatic hydrocarbons (PAHs) and nutrients. Water quality parameters such as biological oxygen demand (BOD), chemical oxygen demand (COD), temperature and pH are impacted (Atasoy et al., 2006; Hatt et al., 2004; Bhaduri et al., 2000; Van Dolah et al., 2008). Similarly, monitoring of hydrological parameters in key catchments has shown drastic changes in flow volumes and peak discharges over the last decades. In rivers, peak flow rates are reported to increase by 100% to 50,000% (Roesner et al., 2001) and flow volumes to have increased by 100% to 5000% (Roesner et al., 2001; Hollis, 1975) in some cases. While establishing urbanisation and industrialisation as the major cause of hydrological and water quality changes in natural water bodies, Section 2.1.1 underlines the role of the different forms of urban drainage discharges in these changes.

2.1.1 WATER QUALITY IMPACTS

2.1.1.1 Urban drainage as a factor of water quality degradation

Based on legislative requirements (European Communities, 2000), the assessment of water bodies at 3000 locations in Scotland based on a wide range of ecological and water quality indicators has found that 44% of the rivers, 34% of the lochs, 15% of the estuaries, 6% of coastal waters and 24% of groundwater bodies have bad to moderate water quality status (SEPA, 2009). This level of degradation has been strongly linked with anthropogenic activities. In Scotland, a correlation coefficient over 0.6 has been reported between urban land use and common pollutants (suspended solids, NH4-N, PO4-P, BOD) found in water bodies (Ferrier et al., 2001). Similarly, water quality monitoring of an urban stream in London found that increases in suspended solids, nutrients and BOD was mainly associated with surface water discharges and combined sewerage systems (Mulliss et al., 1996). Amongst the different types of pollution affecting water quality in receiving waters and including agricultural discharges, discharges of sewage through separate and combined systems, urban drainage has been reported as the fourth most prevalent cause of pollution in rivers and the second most significant for polluted to seriously polluted rivers in Scotland (Marsden and Mackay, 2001). Similarly in the US, diffuse pollution is one of the main source of pollutants, reported as the second most common cause of watercourses degradation (Walker et al., 1999).

2.1.1.2 Pollution characterization

Amongst the pollution inputs to water bodies, a distinction should be made between point source pollution and diffuse pollution:

- **Point source pollution** corresponds to a single and identifiable source of pollution. In urban and rural environments, the main point source pollutants affecting water quality are discharges from Combined Systems Overflows (CSOs) and Waste Water Treatment Plants (WWTP).
- **Diffuse pollution** is defined as pollution arising from land use activities that are dispersed across a catchment, or sub-catchment and do not arise as a process effluent, municipal sewage effluent or farm effluent discharge (Campbell et al., 2006).

Point source pollution can be a major source of pollution (e.g. Gucker et al., 2006; Thaicharoen et al., 2007) and it should be noted that point source and diffuse pollution may be closely related. Indeed, the development of separate drainage as an alternative to combined systems in new developments at the periphery of existing networks lead to a reduction in the discharge flow expected at the CSOs during rainfall events and also to a reduction in the volumes carried to the WWTP. This technique, known as hybrid system, contributed greatly to a potential reduction of CSOs discharges in the context of new developments. However, this marked reduction in point source pollution, came at the cost of more diffuse pollution due to the surface water discharges to water courses.

Despite the fundamentally stochastic nature of diffuse pollution (Rossi et al., 2005), it has been characterised in many different ways. In particular, the concept of diffuse pollution in urban and industrial areas is predominantly characterised by the processes of build-up and wash-off. These processes correspond respectively to the accumulation of pollution on urban surfaces during dry weather and the wash off of these accumulated pollutants during rainfall events. These processes have been the object of characterisation, especially on small urban surfaces. Investigations regarding the build up process have mainly demonstrated that 1) build up rates are more important on road surfaces than on roof surfaces (Egodawatta et al., 2009); 2) the rate of build up is relatively high after an event and the rate reduces gradually as the dry days increase to asymptote to an almost constant load (Ball et al., 1998). Similarly the washoff process has shown to be predominately impacted by rainfall intensity and duration (Egodawatta et al., 2009) for the different surface types considered.

These investigations have allowed (Gupta and Saul, 1996) to observe that, due to the nature of the build-up and wash-off processes, there was “an initial period of stormwater runoff during which the concentration of pollutants was substantially higher than during later periods”. This period has been defined as the “first-flush” and, similarly to the build-up and wash-off process, has been characterised at a small scale on uniform surfaces (Batroney et al., 2010; Kus et al., 2010). In particular Van Metre (2003) has shown that the first 2.6 mm of rainfall falling on roof surfaces were sufficient to mobilise most of the pollutants.

While build up, wash off and the underlying first flush process have been clearly identified at a small scale on uniform surfaces, mainly roads and roofs, the existence of a first flush at the catchment scale presents more difficulties to observe. Investigations conducted at a catchment scale have shown the event maximum rainfall intensity and its appearance from the start of the event (Deletic, 1998), the time of concentration of the catchment and the watershed length (Kang et al., 2008) were largely impacting on a first flush appearance at a catchment scale. Overall, the existence of a first flush at a catchment scale is still largely discussed (Deletic, 1998; Bach et al., 2009).

Despite existence on first flush is still a source of concerns at the catchment scale, strong relationships are found between average pollutant concentrations and the land use at different scales. At a small scale, material deposited and washed off from roofs have shown to be higher in highly urbanized areas (Huston et al., 2009). Similarly average pollutants concentration from roads are related to daily traffic (Kayhanian et al., 2003). At the catchment scale, three key studies have established relationship between average pollutants concentrations and land uses (Duncan, 1999; Gobel et al., 2007; USEPA, 1983). These studies have shown that despite the concentration for the different pollutants measured are very stochastic during the rainfall events and the range of average concentrations reported are very wide, on average, there is a consistency between land use and pollutants concentration.

There is also consistency in the nature and type of pollutants that are expected and recognised for their potential negative impacts on the receiving water-bodies (Eriksson et al., 2007). The list below comprises typical pollutants found in surface water discharges from residential and industrial areas:

Nutrients (nitrogen and phosphates).

Nitrogen, among other forms, can be found as nitrate ion (NO_3^-), ammonium ion (NH_4^+), nitrites ion (NO_2^-), nitrogen gas (N_2), nitrous oxide (N_2O) or ammonia (NH3). The natural distribution of the different nitrogen species are very unequal and depend on complex processes of nitrogen fixation and de-nitrification based on chemical and biological transformations known as the nitrogen cycle. An important point to notice is that, despite being largely available, the nitrogen assimilated by organisms is generally limited to the nitrate and ammonium form which are naturally the limited forms of nitrogen available. The release of anthropogenic nitrogen into the natural environment renders some of these forms of nitrogen available in greater quantities. Although the anthropogenic release of nitrogen is mainly via agricultural practice (66%), industrial and urban activities have an important role in the nitrogen pollution (Dubois de la Sablonières, 1998). Nitrogen water pollution in the urban and industrial environments comes from different sources including leaching from some surfaces (nitrogen is used as colouring process), animal faeces, the decomposition of organic matter and industrial release.

One effect of the release of bio-available nitrogen in greater quantities in the aquatic environment is the growth of vegetation initially limited by nitrogen availability. The increase in vegetation growth leads to the reduction in the oxygen concentration and the level of sunlight penetrating the water – a phenomena known as eutrophication. The process leads to the degradation of the ecosystem (Hessen et al., 1997; Toet et al., 1990).

Eutrophication is largely a result of straightforward migration of the anthropogenic nitrate in the environment. For example, Taylor et al. (2005) report dissolved nitrogen to be over 75% of nitrogen forms in the Melbourne catchment). This migration makes nitrogen available for organisms, including human beings where the water resources are used for potable use. The complications which result from the ingestion of high levels of nitrates vary from stomach disorders to cardio-vascular problems, with various consequences that can be lethal. It should also be noted that combination of nitrates with chlorine, used to purify water, can be particularly harmful for health (Martinelly, 1999).

Phosphorous is available on earth in different forms, organic or inorganic, and can change. Anthropogenic sources of phosphorous is mainly agricultural with two thirds of the nutrient originating from agriculture (Dubois de la Sablonières, 1998). However, several urban or industrial activities can also lead to phosphorous release to the urban environment. Largely used in cleaning products or to reduce corrosion in addition to several applications in the industry, the release of phosphates in the environment affects fauna and flora. Similar to the nitrogen cycle, the release of phosphorous in the environment can cause eutrophication of water bodies where phosphorous is a limiting factor for the growth of aquatic plants. Adsorption of high concentration of phosphates by humans can lead to osteoporosis or kidney problems (Ringe, 2008).

Suspended solids

Although suspended solids can result from natural process such as erosion, urban, agricultural and industrial activities can significantly impact on the amount and composition discharged to the aquatic environment (Rosenwinkel et al., 2001). Originating from erosion, vehicle wear, road breakdown combustion particles and manufacturing, suspended solids are often considered as the main pollutant in storm water (Roesner et al., 2001). In addition to the pollutants they contain intrinsically, suspended solids are reported to have several effects on the fauna in aquatic water bodies as they (Bilotta and Brazier, 2008):

- limit the penetration of light in the water and thereby restrict the rate at which organisms can assimilate energy through photosynthesis;
- increase abrasion and scouring thus damaging exposed respiratory organs and making the organism more susceptible to predation through dislodgement; and,
- affectfoetal developmentwithin eggs by blocking pores and preventing sufficient exchange of dissolved oxygen and carbon dioxide.

Polycyclic aromatic hydrocarbons (PAHs)

PAH's are issued from the combustion of fossil fuel. In the UK, road traffic, with an estimated 470t of PAHs released in the environment for the year 2003 (Napier et al., 2006), has been identified as the major source of PAHs (Wilson et al., 2005). Industries may also emit PAHs into the atmosphere under the form of particles in smoke. The particles are then deposited on urban surfaces and washed off during rainfall events. Biotests on fauna and flora samples reported that PAHs, along with other pollutants, were highly toxic (Baun et al., 2003) and were contributing to the dying of invertebrates in water courses (Beasley and Kneale, 2002). PAHs are mainly found in dissolved form, but their capture in silt traps draining roads have shown that they can be bound to small particles(essentially in the fraction smaller than 45µm (Aryal et al., 2005; Jartun et al., 2008).

Heavy metals

Heavy metals in urban runoff come mostly from the abrasion of material used for the construction of roofs (especially copper and zinc) (Gnecco et al., 2003; Clark et al., 2008; Huston et al., 2009; Schriewer et al., 2008; Lamprea and Ruban, 2008) and from traffic related pollution including fuel combustion, tire wear and brake abrasion (Napier, 2008). Although low levels of heavy metals are necessary for the functioning of almost all flora and fauna, high concentrations are toxic in most cases (Zocche et al., 2010; Curtis et al., 2010; Nagajyoti et al., 2010; Ruciniska-Sobkowiak, 2010). Moreover, heavy metals are concentrated by living species, thus increasing the risk to fauna (including humans) as they migrate through the food chain. Heavy metals are reported in varying forms, depending on the heavy metal considered and the location. Bound to particles, zinc has been found in silt traps draining roof areas (Jartun et al., 2008). Similar analysis of roof runoff in Genoa has found 60% to 80% of dissolved lead issued via corrosion to be bound to particles. However, only 30 to 40% of the other heavy metals surveyed for the same catchment (zinc, copper & cadmium) is bound to particles (Vaze and Chiew, 2004).

It has generally been thought that the removal of suspended solids will account for the removal of most pollutants and thus provide a good indicator of how runoff has been treated (Roesner et al., 2001). This view should be considered within the context of particle size, as it should be recognised that the smaller particles contain a significant part of the dissolved bound pollutants, mainly PAHs and heavy metals. This is due to the fact that smaller particles offer larger surface area to volume ratio and absorb higher concentrations of pollutants such as heavy metal or PAHs as a result (Woodward-Clyde, 1994; Chiew et al., 2004). For example, (McKenzie et al., 2008)) showed that bound heavy metal concentrations increase by a factor 10 to 100 as particle size decreases. In addition, the proportion of dissolved particles is variable, depending on the pollutant considered and how it is generated.

2.1.1.3 Environmental standards

In the context of the Water Framework Directive (WFD), the Member States should achieve the preservation or the restoration of at least good chemical and good ecological status for all water bodies within acceptable socio-economic means by 2015. This approach is consistent with water management objectives of several other developed countries to preserve water resources (Queensland Legislation, 2009; US Senate, 2002). The chemical and ecological statuses are defined from biological, chemical and morphological conditions. The WFD includes five status classes: high, good, moderate, poor and bad with the “high” status defined as the biological, chemical and morphological conditions associated with no or very low human pressure. Assessment of the status is based on the extent of deviation from these reference conditions and is specific to the type of the water body considered (river, lake or coastal water) and its geographical and ecological region. While chemical issues are relatively straightforward to understand, the development of standards supporting good to excellent ecological status in different water bodies present more difficulties to evaluate. In this objective, in the UK, a Technical Advisory Group for the UK (UKTAG) has been established in the view of establishing environmental standards to reach to obtain good to excellent ecological status according to the definition provided by the WFD. At the time of writing the UKTAG produced two major reports investigating the relationship between pollutants types and concentrations with the status of different receiving water bodies. The environmental standards developed in the first phase were translated into legislation in 2009 under The Scotland River Basin District Directions 2009 (Stationery office, 2009) while the second phase is currently under review by the stakeholders. Table 2-1 provides key references to these reports and the associated legislation in regards to the pollutants of interest identified as major pollutants in urban runoff. Unless stated otherwise, the tables referred Table 2-1 can be found in The Scotland River Basin District Directions 2009 (Stationery office, 2009).

	Suspended Solids	Total Phosphorus	Nitrogen
Lochs	25(2)	C2.4 (1) C2.5 (1)	C4.3 (Ammoniacal nitrogen) (1)
Rivers	25(2)	C1.3 (1)	C4.21 (Ammoniacal nitrogen) (1)
Transitional			C3.3 (DIN) (1) C3.4 (DIN) (1)
Coastal waters			C3.3 (DIN) (1) C3.4 (DIN) (1)

Table 2-1: Summary of relevant Environmental Standards for Scotland. (1) (HMSO, 1999) (2) (UKTAG, 2008b).

As mentioned in the UKTAG reports (UKTAG, 2008b; UKTAG, 2008a), care should be taken with the figures given to reach good or excellent ecological status as the figures given are subject to further modifications. Indeed, the development of environmental standards being relatively new for some pollutants, the determination of threshold values for different types of water bodies is not an easy task. To face this drawback, the plan of the UKTAG is to monitor and review the standards after their implementation in the context of the WFD.

2.1.2 *WATER QUANTITY IMPACTS*

The development of impermeable surfaces on a catchment has significant impacts on the hydrology of the flow discharged to receiving water courses. By reducing the potential infiltration into the soil and facilitating runoff routing, the development of impermeable surfaces lead to an increase of the volumes discharged and higher peak runoff rates (Mulliss et al., 1996; Roesner et al., 2001) as illustrated in Figure 2-1. In the meantime, the reduction of permeable surfaces can lead to a reduction of the groundwater recharge (Duque et al., 2002; Suresh, 1999).

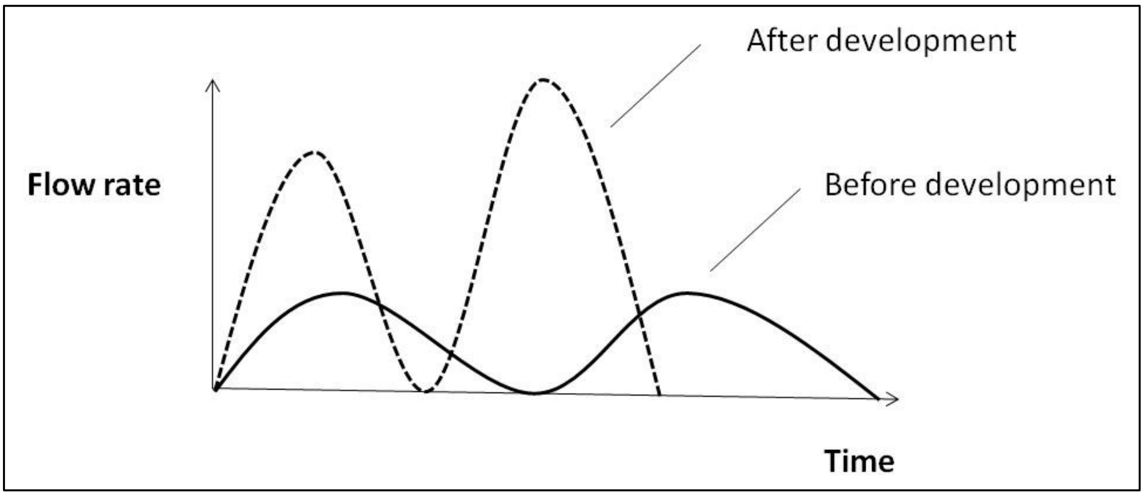


Figure 2-1: Urban impacts on discharged flow volumes (Roesner et al., 2001) (modified)

These modifications of the hydrologic cycle can have different impacts depending on the catchment characteristics as follows:

- A risk of increased downstream flooding, mostly depending on river and catchment configuration (e.g. Nirupama and Simonovic, 2007). In the absence of dedicated structures to attenuate the runoff, protection against flooding, such as the construction of embankments or provision of structures to store the flow, might be needed (Scottish Executive, 2004).
- A modification of the channel hydrology leading to either incision or widening of channels depending on stream characteristics (Clark and Wilcock, 2000; Jeje and Ikeazota, 2002). In addition, high flow volumes associated with a high concentration of suspended solids impact on aquatic and riparian habitat (Section 2.1.1).

2.2 OFFSETTING URBANISATION IMPACT ON THE WATER CYCLE THROUGH THE USE OF SUSTAINABLE DRAINAGE SYSTEMS (SUDS)

When drained by a separate network, adverse impacts of urbanisation described previously can be offset. Solutions can be used to provide water quality treatment to the runoff, help in the recharge of the groundwater, and compensate for the increase of runoff rates and volumes before the runoff is discharged to the receiving water course. Techniques fulfilling these objectives can represent a wide variety of different solutions usually referred to under the generic name of SuDS (Sustainable Drainage Systems) in the UK, Low Impact Development (LID) or Best Management Practice (BMP) in the US.

2.2.1 THE SUDS TRIANGLE PHILOSOPHY

The principal aim of SuDS is to provide surface water with treatment before discharging it to the receiving water body, manage water quantity by attenuating runoff and, where possible, provide amenity and biodiversity to the surroundings. These three key objectives are known to form the three sides of an equilateral triangle presented as the SuDS triangle (D'Arcy and Mclean, 2009).

The water quality side of the triangle is achieved by treating the runoff before discharging it to a receiving water body. The removal mechanisms fall mainly in to three categories: physical, physico-chemical and biological removal. The physical removal of pollutants takes place via sedimentation, filtration or volatilisation. Removal by sedimentation and filtration, affected by particle size and density, are the primary removal mechanisms through which the pollutants are retained. The other processes help with the degradation of particulate pollutants captured by sedimentation and filtration but also with the degradation of dissolved and particulate pollutants that are captured in permanent pools. The biological removal is achieved by microbial degradation, plant and algal uptake. Physico-chemical processes include adsorption, flocculation, precipitation, ion exchange and photolysis. While ion exchange and photolysis degrade the captured pollutants, adsorption, flocculation and precipitation may affect the sedimentation and filtration processes by facilitating the removal of dissolved pollutants through the removal of suspended solids (Scholes et al., 2008). The modelling of water quality parameters is discussed in Section 2.1.1.

The water quantity side of the triangle is achieved by 1) reducing the peak of runoff by providing temporary storage of the runoff or the slowing down of the runoff; 2) reduce the quantity discharged in rivers and 3) recharge groundwater by infiltrating the runoff.

The third side of the triangle is concerned with amenity and biodiversity. SuDS, by providing water treatment and attenuation, prevent the degradation of the biodiversity in watercourses by preventing harmful pollutants to have an impact on the natural environment. The protection of the biodiversity is thought to have a large impact on the activities and perception of residents (Apostolaki and Jefferies, 2005; Apostolaki et al., 2006). The activities vary from one site to another but can include pet walking, boating, swimming and all the activities which take place along the water body that would not have occurred if the site wasn't rendered attractive, safe and pleasant looking by the SuDS. These activities, along with landscape improvements are often referred to under the generic name "amenity". While these benefits in terms of amenity and biodiversity are a consequence of the water quality and quantity improvements provided by the use of SuDS devices, the SuDS can provide amenity and biodiversity at a more local scale. Indeed, certain types of SuDS, mainly those including a permanent pool of water and/or vegetation are thought to have a potential to bring amenity and biodiversity in cities. Thus, implementing SuDS could help in fulfilling environmental regulator aims and duties with regard to conservation, biodiversity and sustainable development in relation to habitat (SEPA, 2000) by providing natural looking water features and associated green spaces and thus contribute to the well being of residents (Greenspace Scotland, 2008).

The potential amenity in general has to benefit residents has been investigated for different structures ranging from the benefits of green spaces (Snyder et al., 2007), beaches and ocean in close proximity to dwellings (Hamilton and Morgan, 2010) or more closely by river management improvements (Apostolaki and Jefferies, 2005). Similarly, the amenity of SuDS structures has been investigated by different authors. For example, (Yuen and Hien, 2005) investigated the perceived amenity of green roofs in high density areas and have shown that their presence was valued positively by residents who have acknowledge their potential amenity value. The perception of rainwater harvesting in residential areas has been investigated by (Ward et al., 2009), who demonstrated that residents were keen on reusing the water from their own roof for gardening purposes but reluctant to recycle runoff from other sources. In addition to this research, Apostolaki and Jefferies investigated public perception of SuDS which included a permanent water body (Apostolaki and Jefferies, 2005). Overall, the survey demonstrated that there was significant interests in ponds. When questioned if it was felt SuDS could increase or decrease property value, respondents suggested the presence of a well established pond could increase residential property value by up to 10%.

Similar to amenity, an increased biodiversity can be found as a result of SuDS implementation to mitigate urban, industrial and agricultural activities. The increased biodiversity is associated with both receiving waters and the SuDS devices. The biodiversity is evaluated through a campaign of species identification and counting. This approach has been applied to most of the natural water bodies in Scotland following European recommendations and has resulted in the categorisation of biodiversity indictors for different natural water bodies throughout Scotland (SEPA, 2009). Similar approaches on identifying and counting species in close proximity to SuDS devices have been undertaken on several occasions. For example, green roofs have been identified as a potential habitat for birds (Fernandez-Canero and Gonzalez-Redondo, 2010) including endangered species (Grant, 2006) and invertebrates (Kadas, 2006). SuDS with permanent pools of water body have been identified as a great source of biodiversity in urban areas, especially for the conservation of invertebrates and birds (Le Viol et al., 2009a; Karouna-Renier and Sparling, 2001; Scher and Thiery, 2005; Vermonden et al., 2009). However, the biodiversity associated with SUDS which have permanent pools should be considered within the context of their primary function of attenuating and treating runoff. Biodiversity studies around regional controls such as ponds and wetlands have shown that the pollutants contained in the runoff could affect the it (Bishop et al., 2000a; Bishop et al., 2000b; Snodgrass et al., 2008; Le Viol et al., 2009b). The consequences vary from a change in species density to a threat to some, especially the ones higher in the food chain such as birds (Sparling et al., 2004). Despite the absence of a clear relationship between species frequency and water quality (Bishop et al., 2000a), poor water quality is indubitably the cause of a reduced biodiversity potential in comparison to natural environments. To enhance the potential biodiversity, the use of source controls is highly recommended as a means to protect biodiversity in regional controls from background pollution and accidental spills (Helfield and Diamond, 1997). The potential for biodiversity at regional controls would then be maximised if its role was constrained to the removal of very small particles, “polishing” the treatment provided upstream by source and site controls (Wong, 2000).

2.2.2 The SuDS treatment train

Complementary to the notion of SuDS triangle defined in the previous section, the environmental regulators (SEPA, 2006; Environment-Agency, 2007) recommend using the techniques in series as illustrated on Figure 2-2. These combinations of different techniques in series are known to form the treatment train and is widely encouraged by environmental regulators (Environment-Agency, 2007; SEPA, 2006) as it has the following benefits:

- Improved degradation of the pollutants: the use of different SuDS techniques implies that different removal mechanisms (physical, physio-chemical and biological) take place at each stages of the treatment train in a manner that is complementary and adds value. As the different pollutants do not have the same sensitivity to different removal mechanisms, the use of contrasting techniques in series will improve the opportunity for the whole range of pollutants to be removed and degraded. Barrett compares SUDS performances for different pollutants (Barrett, 2005). The methodology is based on a linear regression analysis of paired influent and effluent Event Mean Concentration, allowing performance for different SuDS, source and site controls, to be compared on the same basis, independently of influent concentration. The output of the survey conducted on retention ponds, swales and sand filters has shown that sand filters were performing the best for the removal of TSS whereas retention ponds were achieving better performance for the removal and degradation of nitrate.
- A better management of the risks associated to an accidental spill: by providing treatment closer to the source of pollution and by avoiding the dilution of the pollutant with other sources of pollution, the treatment achieved is generally better (Barrett, 2004).
- The shock load effect on regional controls is reduced: the use of SuDS in series, and in particular of source and site controls to provide upstream treatment before the water is discharged in the regional control reduces the risk associated with excessive pollutant loads being discharged into regional controls. The avoidance of heavily polluted discharges into the regional control maximizes the opportunities for wildlife to develop and maximize the potential amenity offered by regional controls such as ponds and wetlands. Comparison of fauna and flora indicators for wetlands in natural conditions and for wetland receiving important loads of urban runoff have shown significant differences in the type and number of individuals for the different sites (Helfield and Diamond, 1997). While the study underlines the relatively low tolerance of fauna and flora for urban pollutants, it also underlined the need for an upstream control in the case biodiversity restoration is a dual objective with water quality restoration.
- A better management of the risks associated to an eventual failure of the system: the consequences associated with the malfunction of a system element are limited because SUDS either upstream or downstream of the system will provide treatment before the runoff is discharged to the receiving water body. Failure of

the system may, for example, result from poor design or overloading due to excessive urban creep.

- Longer SuDS lifecycle: providing treatment to the runoff prior to it entering site or regional controls reduces the pollutant load - especially suspended solids. The filling or clogging of regional controls is then reduced and the design life is extended. Investigations on SuDS pond at the Dunfermline Park presented in Section 2.2.4 has shown that the need for maintenance estimated when pond volume was reduced by 25% was varying between 17 and 98 years (Heal et al., 2006). While this underlines high variability in SuDS maintenance needs, it demonstrates how life cycle could be extended by using upstream controls allowing the load of TSS discharged in the regional control to be reduced.

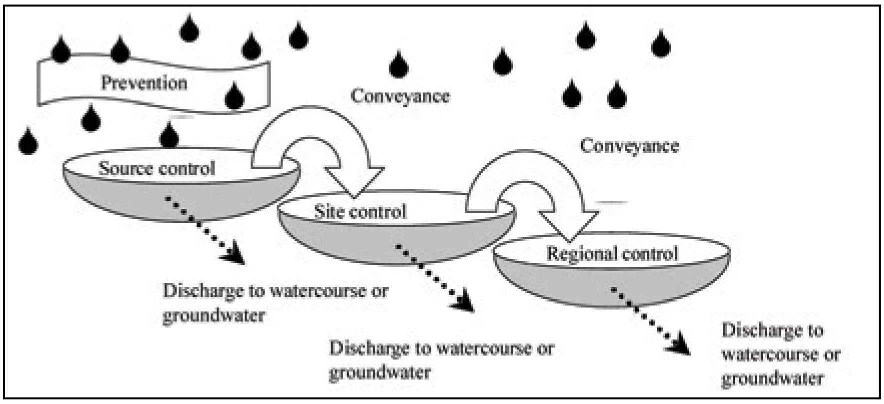


Figure 2-2: SuDS treatment train (CIRIA, 2007)

The different SUDS techniques available to form a treatment train usually fall into five categories depending on their location in the catchment described as follow:

Prevention: This consists of using good site design and housekeeping measures to prevent runoff. Where runoff does occur, measures should be taken to prevent it from being unnecessarily polluted.

Source controls are defined as devices as close as possible to the source of pollution and/or runoff. These include all pervious pavement systems and the use of SuDS at the building curtilage such as water butts, water harvesting and green roofs. The use of these techniques allows the treatment, attenuation and infiltration of runoff before passing any outflow downstream. These techniques can clearly be used upstream of any other techniques - either other sustainable or conventional drainage systems (Swan, 2002).

Conveyance systems are systems used to transport runoff from the catchment in direction of the receiving water body. Swales are the primary conveyance technique available as shown in Section 2.2.3.5 but adaptation of other techniques can also provide a solution for the conveyance of runoff from a point to another.

Site controls are devices for the management of water in a local area or site. In contrast to regional controls, site controls drain only a limited part of a site or catchment.

Regional controls manage runoff from one or several sites. Regional SuDS are similar to site SuDS but apply to larger areas.

2.2.3 SuDS DEFINITIONS

A wide range of different SuDS devices can be used for the treatment and the attenuation of storm water runoff. The section below presents the SuDS techniques sorted by their primary functions, either for the removal of pollutants or the management of water volumes.

2.2.3.1 Filtration techniques

Filtration is considered as the main mechanism by which pollutants contained in the runoff can be removed. Filtration techniques allow the removal of suspended particles in runoff using a substrate. Dissolved pollutants may also be removed provided they are bound to suspended solids. The following techniques are considered as particularly adapted for filtration:

Pervious pavement

The term pervious pavement refers to pavement where water can either infiltrate through the entire surface of the material (porous pavement) or between the spaces left between the material (permeable pavement). This distinction is largely used throughout the literature (Scholz and Grabowlecki, 2007) but the definition of sub-categories is less clear, as there are a large variety of different types of permeable pavement. The classification system described below is adapted from that established by (Pratt et al., 2002).

Porous pavement allows the infiltration of water across its entire surface and includes:

- Open textured soil or granular material: consisting of gravel or similar material which is often reinforced using geo-synthetic cellular systems.
- Geosynthetic gravel/grass protection systems: consisting of modular interlocking plastic paving systems in filled with gravel, grass or aggregate.
- Small porous elemental surfacing blocks: consisting of porous block paving.
- Continuous-laid porous material: consisting of porous asphalt, concrete or resin bound aggregate.

Permeable pavement is formed of material that is itself impermeable to water, and includes:

- Surfacing blocks: consisting of either large pre-cast blocks or small elemental surfacing blocs with small gaps which allow infiltration.
- Continuous laid permeable material: consisting of concrete systems that provide a surface with large voids for infiltration.

Permeable pavement can be relatively complex in terms of the placement of the different materials which underlie the surface. However, four main components which influence the structural and/or hydraulic design can be identified.

- Pavement layer.
- Geotextile or geomembrane: A geotextile layer may be used to separate the different layers constituting the permeable pavement. Where geomembranes are used it is to help prevent infiltration from the underlying soil (sub-grade) to the groundwater. A geotextile may also be specified to improve runoff filtration, thus improving water quality.
- Sub-base: Permeable pavements are laid on a sub-base designed to sustain traffic loading without excessive deformation. The sub-base can also be designed for water storage. When water storage and structural design are both considered, the more restrictive design is generally adopted. The sub-base is usually comprised of aggregates.
- Sub-grade: The sub-grade is normally made up of the local soil and its infiltration capacity greatly influences the overall design of the permeable pavement.

Once the general system type has been chosen, the design of the different layers is based on hydraulic and structural requirements.

In addition to the filtration process, pavements can, if the conditions allow, be designed to infiltrate the water (type A) and/or drain the eventual excess of water (type B). In case infiltration is prohibited, protection measures have to be put into to place to avoid the infiltration of the water in the soil and the water being completely drained (type C).

Trenches

Trenches are shallow excavations between 1m and 2m depth filled with stones. The gaps between the stones create a temporary storage volume. The water is infiltrated into the soil through the bottom or the sides of the trench (Infiltration trench) or collected with a perforated pipe and discharged to a watercourse or any other drainage system element (Filter trench).

The design of trenches is a compromise between water quality and quantity objectives:

- The material used to fill the trench acts as a filter by removing particles. Finer filter material can increase filtration performance by maximising the contact duration between water and material. However, fine material has a lower void ratio.
- The trench is acting as a storage device and storage capacity is increased with a high void ratio in the material.
-

Normally, Darcy's law and infiltration capacity are used to design the trench and the underlying pipe if necessary to make sure the trench is not flooding for the design return period (CIRIA, 2007).

2.2.3.2 Infiltration techniques

Infiltration techniques provide the advantage of reducing the volume of water that needs to be discharged into the receiving watercourse and provide an opportunity for groundwater recharge. Infiltration techniques contribute to the improvement of water quality by two means:

The infiltrated volume of runoff at source and site controls generally comes from relatively clean runoff sources such as roofs (Bettess, 1996). Infiltration of the runoff at an early stage from these clean sources prevents runoff from mixing with more polluted runoff sources and thus avoids dilution of pollutants. Less diluted pollution reaching regional control facilitates and improves treatment provided by regional controls (Barrett, 2004).

The infiltrated volume is filtered by the soil thus removing particles carried by the runoff. From a hydrologic point of view, the volume infiltrated reduces the volume discharged to the river. However, land use, catchment and soil characteristics may limit the use of this technique.

The infiltration of water into the soil can only be realised if the infiltration rate of the soil is sufficient. Table 2-2 shows typical infiltration rates for various soil types. Precise rates are usually determined using an infiltration test (BRE, 1991).

Soil type	Range of infiltration rates (x10^{-3} m/s)
Gravel	10 – 1000
Sand	0.1 – 100
Loamy sand	0.01 – 1
Sandy loam	0.05 - 0.5
Loam	0.001 - 0.1
Silt loam	0.0005 - 0.05
Chalk	0.001 – 100
Sandy clay loam	0.001 - 0.1
Silty clay loam	0.00005 - 0.005
Clay	<0.0001
Till	0.00001 - 0.01
Rock	0.00001 - 0.1

Table 2-2: Infiltration rates for different soil types (CIRIA, 2007).

Although runoff is infiltrated, the migration of particles into the soil is limited. Depending on ground conditions, high pollutant concentrations are normally only found in the first few centimetres of the soil while decreasing levels are found with increasing depth (Legret et al., 1996). However, runoff investigations have shown that significant amounts of pollutants, mainly dissolved, can still migrate into the soil with runoff (Murakamia, 2008). These pollutants, despite having a reduced concentration, can have substantial loading factors when recharge rates in the soil are high (e.g. infiltration basins) (Fischer et al., 2003). These impacts present groundwater pollution risks and can severely affect water abstraction in some cases. To counter these drawbacks, it is generally recommended that infiltration devices either drain surfaces with low levels of pollutants such as roofs or manage flows which have already undergone a level of treatment (CIRIA, 2007). To protect further sensitive groundwater and abstraction zones, infiltration might be prevented by the environmental regulator to protect ground water resources (Bettess, 1996).

Excessive runoff infiltration can have significant impacts on the surrounding buildings. Consequently and to prevent differential sinking, infiltration practices are regulated and prohibited within 5m of buildings and roads in order to prevent damages (HMSO, 1991).

Soakaways

These are shallow excavations, typically up to 4m depth, into the ground designed to store and dispose runoff by infiltration. Soakaways draining less than $100m^2$ are traditionally square or circular pits filled with rubble or lined with dry-jointed brickwork or pre-cast perforated concrete ring units. Soakaways can take the form of trenches, especially for areas larger than $100m^2$ to maximize infiltrating area. Soakaways are typically designed to infiltrate flows resulting from a 10 year return period based on infiltration capacity of the surrounding soil (BRE, 1991).

Infiltration basins

Infiltration basins are vegetated depressions designed to store runoff and infiltrate it gradually into the ground. In order to avoid the clogging of the device with pollutants, they are usually used to drain relatively clean runoff, either from roof areas or other SuDS devices (CIRIA, 2007).

Sand filters

Sand filters treat the runoff by filtering it through a sand bed before infiltrating it into the soil. The sand filter can be of different types:

- Surface sand filter: the water is stored in an open structure (e.g. pond) before being infiltrated in the sand bed.
- Underground sand filter: The water is stored in an underground storage (e.g. tank) before being filtered through the sand.

In both cases, the sand bed provides treatment to the water by filtration before infiltrating it into the soil.

2.2.3.3 Retention techniques

The retention of runoff promotes pollutant removal through sedimentation and the opportunity for biological uptake and physic-chemical mechanisms to reduce dissolved pollutant concentrations. In principle, the volume is retained in the SuDS during inter-events before another event input water into the system: the clean runoff is progressively released in the system and replaced by fresh runoff needing treatment. The maximum volume of water that can be permanently stored is known as permanent pool or captured volume and is a key element in the design of water quality control of SuDS based on the notion of treatment volume (Vt) detailed in Section 2.3.3. In all cases, peak flow rate and runoff volumes are reduced by the temporary storage of runoff and possible infiltration. Different techniques promote water retention:

Ponds

Ponds are site or regional control facilities including a permanent wet storage volume designed to capture frequent rainfall events while an extended depth can be used for water attenuation purposes. Ponds include a sediment forebay to avoid sediment dispersion and a shallow zone supporting vegetation to provide water treatment by filtration and nutrient removal by adsorption. Low side slopes (maximum recommended 1:4) and barriers around the pond provides safety for residents (CIRIA, 2007; Scottish-Water, 2007).

Wetlands

Two main types of wetlands can be identified:

1) Surface flow wetlands are marshy areas, covered almost entirely in aquatic vegetation and comprise shallow ponds. They remove pollutants by adhesion to vegetation, aerobic decomposition and sedimentation of pollutants through an extended detention period (CIRIA, 2007);

2) Sub-surface flow wetlands, less common, are areas where water flows horizontally or vertically through the substrate. Pollutant removal occurs through the filtration by the media and uptake by plants (Schutes, 2001).

While pollutant removal processes achieve better results with sub-surface wetlands, the flow treated is less than with surface flow wetlands and explains the relatively low uptake of sub-surface flow wetlands.

2.2.3.4 Attenuation and storage techniques

Not necessarily designed to provide treatment to the water, attenuation can be provided in addition to other techniques, especially ponds, wetlands and infiltration basins where an additional volume can be allocated to the attenuation of a design return period. The stored volume is either discharged slowly into the receiving water course at the greenfield runoff rate (Mashall and Bayliss, 1994) or infiltrated into the soil. However, attenuation can also be provided by dedicated structures:

Sub-surface Storage

Tank storage consists of storing water collected for attenuation and/or reuse purposes. There are three main types of sub-surface storage possible:

- Water butts are roof water storage devices that are commonly used for the purpose of collecting rainwater from roofs for gardening. The devices comprise storage volume (normally a barrel) designed to store water that can be reused and an additional storage volume designed to attenuate runoff where the discharge is limited by a throttled outlet. A second outlet which is designed to pass water to the downstream drainage system acts as an overflow (CIRIA, 2007).
- Rainwater harvesting are also roof water storage devices collecting water from a single or a group of dwellings. The water is then reused for non potable use (Ward et al., 2008). Potable reuse of water stored in rainwater harvesting devices can be envisaged where the water shortage is high provided adequate treatment is provided to the water (Ashworth, 2005).
- Underground storage structures are usually used to drain larger areas and are designed for attenuation or, in some cases, reuse (provided the water drained is not severely polluted).

Storage devices which are designed to also allow water reuse must be treated carefully at the design stage as they cannot be assumed to be empty at the start of the design storm (Vaes and Berlamont, 2001). When designed for attenuation, the system is designed based on the required attenuation period. However, when designed for both attenuation and alternative water reuse, their design may appear conflicting and a probabilistic approach to maximise their performance can be adopted (Lee et al., 2000).

Green roofs

Greens roofs are multilayered systems covering roofs. They essentially comprise a substrate on which vegetation may grow and hence provide rainwater storage, attenuation and evapo-transpiration. Green roofs may be broadly categorised in to two types (CIRIA, 2007):

- The extensive green roofs have a substrate layer of 20 to 200mm where low growing plants such as succulents, herbs, grasses and mosses may grow.
- The intensive green roofs are landscaped environments with a substrate of 150 to 1500mm. The roof can include water features and storage for irrigation purposes and require a significant ongoing maintenance. The implementation of intensive green roof usually requires improved building design so as to cope with the extra weight of soil, vegetation and water.

The reported volume of water resulting from an individual rainfall event that can be stored by green roofs is highly variable and depends mainly on substrate depth, roof slope (VanWoert et al., 2005; Getter et al., 2007) and the antecedent dry period (Stovin, 2008). Commonly accepted values for green roof design are summarised in Table 2-3.

Substrate depth (mm)	Water storage capacity (l/m²)
130-165	25-35
250-350	75-115
>450	~140

Table 2-3: Typical retention values for green roofs with different substrate depths. Adapted from (CIRIA, 2007)

The quality of the runoff from green roofs is linked to their maintenance. Significant water quality benefits can be achieved in urban environments by green roofs mainly by the removal of very small particles deposited on green roofs. However, use of fertilizers due to maintenance requirements can be a significant source of pollutants (Emilsson et al., 2007).

As well as their role in rainwater management, green roofs have been reported as having other advantages which include:

- acting as an air purifier by capturing the pollutants in the air (Yang et al., 2008);
- being beneficial in terms of insulation (Wong et al., 2003); and,
- performing as a ecological habitat (Grant et al., 2003; Kadas, 2006);

Detention basins

Detention basins are site or regional surface storage devices which provide flow control through attenuation of storm water runoff. Detention basins are normally dry, and in certain situations the land may also be used as a recreational facility (Lee and Li, 2009). Used to attenuate storm water resulting from 10 to 200 year return period events, the design includes low sides slope for safety reasons (maximum 1:4), an outlet restricting the flow and allowing the basin to fill and an emergency spillway to bypass the basin once it is full. The basin may include a pre-treatment forebay to improve water quality treatment and reduce maintenance activities (CIRIA, 2007; Scottish-Water, 2007).

Sub-Surface storage

As their benefits in terms of water quality are limited, sub-surface storage is often not seen as a SUDS device by the Environmental Regulators. However, subsurface storage structures can help attenuate runoff by providing a temporary storage volume. Using high void ratio geo-cellular systems, the water is temporarily stored before being discharged through a throttled outlet or infiltrated into the soil where local conditions permit. The subsurface storage devices should be designed to take into consideration the eventual load due to any infrastructure built on the surface (CIRIA, 2007; Scottish-Water, 2007).

2.2.3.5 Conveyance techniques

The term conveyance is used for SuDS provide a means to transport runoff from one point to another, thus preventing the use of pipe systems. Some SuDS can be adapted to convey the runoff (e.g. linear wetland), but examples of such adaptations are limited and conveyance systems are primarily swales or, to a lesser extent, trenches.

Swales

Swales are SuDS techniques used to convey water from source to site and site to regional controls. These are grassed depressions with a minimum recommended base width of 0.5m and 1 in 3 side slopes. To avoid erosion and the resultant dispersal of pollutants, runoff ideally enters the swale laterally rather than at a single point. They are ideally suited to relatively flat areas, and are best installed with low gradient sides and dense vegetation as this slows the flow and improves the removal of sediments and facilitates infiltration. Swale performance can be improved by incorporating a filter bed overlaying a drain system. This provides additional conveyance and improved treatment by filtration (dry swale). The swale can also incorporate a permanent water body providing marshy conditions where improved treatment of runoff is provided by retention (wet swale). A geo-textile can be used where infiltration into the soil is not desirable (CIRIA, 2007).

2.2.4 CASE STUDIES

Despite large scale implementation of SuDS in Scotland, their implementation is very often characterised by the implementation of regional control only. Thus, the techniques described previously and the associated philosophies (the treatment train and the SUDS triangle) are poorly implemented. The causes leading to a restricted implementation of SuDS techniques are further analysed in Chapter 3.

Contrastingly, the treatment train philosophy and the SuDS triangle philosophy have been implemented in some sites in the UK. This section reviews two pilot UK sites:

- The Dunfermline site is presented as it is often considered to be the first where SuDS were implemented at a large scale and was used as showcase as a result. Despite being developed prior to the current legislation and design guidance, Dunfermline has paved the way for SuDS implementation in the UK.
- The second site, Hopewood Park, was developed more recently and, despite being simplified to satisfy stakeholder requirements, employs the treatment train philosophy. Additionally, like the Dunfermline site, instrumentation was installed to monitor performance.

Dunfermline Eastern Expansion (DEX): this large-scale project is a key development which lies to the east of Dunfermline. The site has been developed as a mixture of residential, industrial, commercial and recreational areas. Flooding problems in the downstream area, water quality issues due to urban runoff or wrong connection to the separate system has led to the integration of SuDS in the development expansion area as a planning condition (D'Arcy and Robin, 2007). A series of source, site and regional controls were implemented encompassing the use of permeable pavement, kerbs and swales, extended detention basins, retention ponds, wetlands and infiltration controls where soil conditions were favourable (Figure 2-3). Based on four years of rainfall data (1991-1994), SuDS facilities were designed using a storm simulation based on the notion that they should be able to capture 90% of all rainfall events without any outflow (Roesner et al., 2001).

Monitoring of DEX SuDS facilities in the years subsequent to their construction has shown that they achieve satisfactory hydraulic control and water treatment. Sedimentation rates of 0.4 $cm.yr^{-1}$ for the Lindburn pond, integrating an upstream treatment train, is lower than the sedimentation rate of $1cm.yr^{-1}$ for the Halbeath pond designed as a end-of-pipe solution and draining a catchment with similar characteristics. This finding has a significant impact on the maintenance requirements of the ponds as expected need for sediment removal is 17 years for the Lindburn pond and 98 years for the Halbeath pond. It was concluded that the use of a treatment train reduces the amount of suspended solids and bound pollutants reaching regional controls, and hence reduces maintenance requirements (Heal et al., 2006).

Figure 2-3: Layout of Dunfermline

Hopwood Park: Hopwood Park is a 9 ha project located in England encompassing car parking, coach parking, HGV parking and associated fuelling area. The treatment train philosophy for this site has been implemented following environmental regulator advice and includes the use of filter strips, swales, trenches, ponds and wetlands (Figure 2-4). Monitoring of the different treatment trains has shown excellent water quality and hydrological performance (Figure 2-5) (Heal et al., 2009):

- Flow monitoring has shown significant and progressive flow attenuation along the treatment train which complies with the design objective of achieving greenfield peak runoff conditions by attenuating 1 in 25 year rainfall event.
- Water quality monitoring has shown a progressive reduction of the pollutant load as the runoff runs through the different SuDS devices. Overall, all the pollutants investigated and monitored demonstrated a reduction in concentration as they pass through the different components of the treatment train. Statistically significant differences form this established rule is for NH4-N at the coach car park, but the excess measured has been attributed to lorry drivers urinating near their vehicles.

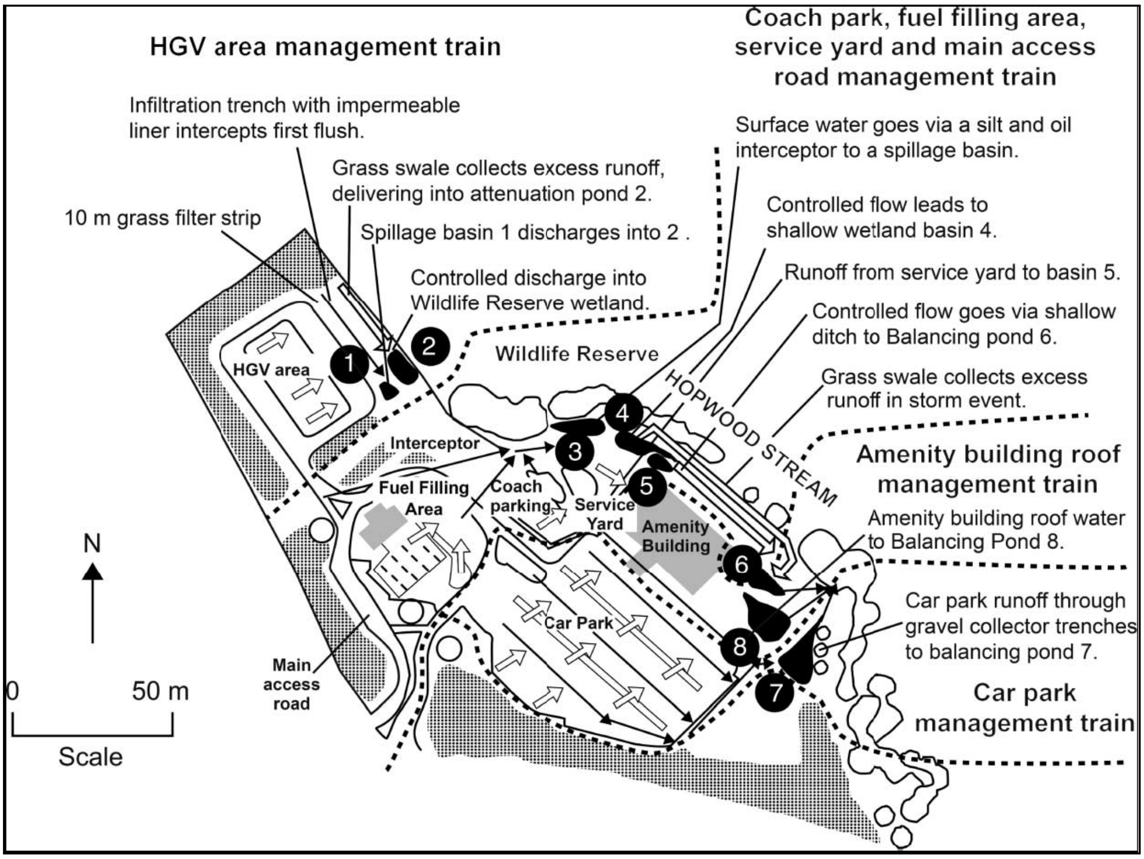


Figure 2-4: Layout of Hopwood Park Motorway service and SuDS management trains (Heal et al., 2009)

Sample point	NH_4-N ($mg\,l^{-1}$)	BOD ($mg\,l^{-1}$)	TSS ($mg\,l^{-1}$)	Total Cu ($\mu g\,l^{-1}$)	Total Zn ($\mu g\,l^{-1}$)
HGV park management train					
HGV park runoff	30.8 (38.6)	81.4 (95.7)	429 (477)	343 (367)	2,438 (3,486)
Pond 1 inlet	7.38 (5.86)	7.46 (7.48)	22.5 (21.0)	22 (10)	358 (855)
Pond 1 outlet	4.94 (3.29)	4.78 (4.28)	13.1 (17.3)	15 (7)	78 (43)
Coach park, fuelling area, main access road management train					
Interceptor outlet	0.37 (0.49)	11.4 (9.94)	78.5 (91.0)	45 (43)	230 (200)
Pond 3 outlet	0.76 (0.89)	12.2 (10.3)	30.1 (29.8)	27 (25)	167 (99)
Pond 4 outlet	0.55 (0.44)	7.39 (5.17)	22.2 (14.6)	15 (11)	100 (55)
Pond 6 outlet	0.20 (0.21)	3.50 (5.50)	8.04 (4.94)	5 (3)	27 (19)
Car park management train					
Car park runoff	0.15 (0.22)	2.19 (1.77)	11.1 (10.5)	11 (8)	18 (31)
Pond 7 outlet	0.08 (0.11)	1.91 (0.91)	16.8 (19.3)	11 (8)	32 (37)

Figure 2-5: Mean (Standard deviation) of the measured chemical parameters in water samples collected along treatment trains (Heal et al., 2009)

2.3 CURRENT SUDS DESIGN FOR SCOTLAND

This section aims to review current SuDS design in Scotland. The key stakeholders along with the regulations and the guidance available in Scotland are presented.

2.3.1 KEY STAKEHOLDERS

The drainage of rainwater, by the time it is reaches the receiving water body, needs to be managed according to the needs and requirements of several stakeholder involved at different stages of the runoff management. This section aims to present the key stakeholder responsibilities and interests in implementing SuDS:

Sewerage undertaker: represented by Scottish Water in Scotland, they have the statutory duty to effectively drain domestic sewage and surface water runoff from roofs and paved areas within the curtilage of premises (Sewerage (Scotland) Act 1968). This responsibility includes pipe network and adoption and maintenance of public SuDS if they are built to agreed standards (Scottish-Water, 2007) under the WEWS act (Scottish-Executive, 2003).

Environmental regulator: Represented by SEPA in Scotland, the environmental regulator aims is to "protect or enhance the environment, taken as a whole, in order to play its part in attaining the objective of sustainable development" (HMSO, 1995). Within the context of urban drainage, they are responsible for ensuring that good practice is followed regarding runoff discharges and, as a result, strongly encourage the use of SuDS. SEPA also has a supervisory duty regarding all flood risks in Scotland

Homeowners and residents: This group are responsible for the drainage network within the private curtilage, including pipe network and possible SuDS. Living in close proximity to SuDS, they are concerned with potential flooding issues caused by the drainage network. They also have an interest in the amenity and biodiversity that SuDS could potentially bring.

Local authorities: Local authorities are responsible for planning development, local land drainage and most roads.

Developers: The developers have the duty, under the Roads (Scotland) Act 1984 to provide roads and associated drainage systems for new developments.

Road authorities: This group is responsible for road drainage and can either be represented by:

- Transport Scotland for the trunk road network, including strategic roads and motorways; or,
- Local authorities adopting roads built by the developers under the Roads (Scotland) Act 1984.
- Road authorities may connect to publicly owned SuDS maintained by Scottish-Water under Section 7 of the Sewerage (Scotland) Act (1968).

2.3.2 Regulations and guidance

The European Water Framework Directive (WFD) intends to create a framework for the management and the protection of waters. Its objectives are to reach a good ecological and biological status for all water bodies, including surface and groundwater by 2015. While the WFD gives an outline of the objectives to meet for the member states, the set up and transposition in state legislation gives way to different interpretations (Malgrat et al., 2005).

The WEWS act (Stationery office, 2003) represents the main transposition of the WFD into Scottish law. Of key importance, is that the use of separate systems and SuDS is mandatory for virtually all new developments built after 2007. It should be noted here that although the legislation addresses potential issues linked to new developments, nothing is expected for urban catchments built before the legislation came into force.

This is important as these developments are responsible for a considerable part of the pollution encountered in watercourses (Butler and Davies, 2009).

Administered by SEPA, The Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR) (Stationery office, 2005) regulate all discharges into the water environment, including groundwater, through a system of licences, registrations and general binding rules. Part of the CAR regulation, the General Binding Rule 10 (GBR 10) states that all water runoff from areas constructed after the 1st April 2007 must be drained by a Sustainable Urban Drainage System unless the runoff comes from a single dwelling or the area drains to a costal water or the drainage is impossible.

While decisions on developments are usually made at a local level, national guidance supports and encourages the use of SuDS: PAN79 (Scottish Executive, 2006) encourages the use of SuDS as a strategy to comply with the objectives of sustainable development. PAN61 (Scottish executive, 2001) clarifies the roles and responsibilities of the different stakeholders involved in implementing drainage facilities and links legislation and mandatory requirements regarding drainage. PAN61 and PAN79 are due to be updated by a consolidated PAN which should further encourage the use of SuDS. The use of SuDS are also encouraged at the national level as a means to deal with flooding issues by temporarily storing the runoff and thus limit off-site flood risks (Scottish Executive, 2004).

The implementation of SuDS is supported by guidance to the attention of the stakeholders. Among the numerous guidelines available, the following guidance is commonly used.

The SuDS Manual (CIRIA, 2007)

The SuDS Manual (CIRIA, 2007) is actually the main reference document in Scotland and offers an up to date database on SuDS characteristics. Numerous matrices are available to compare SuDS devices using different criteria. Recommendations on SuDS that can be used are made based on land use, site and catchment characteristics, SuDS hydraulic and treatment performance, community, environmental and amenity performance. Regarding the treatment train, the SuDS Manual gives rough recommendations on the number of SuDS devices that can be used in series to treat runoff to a sufficient level. This guidance is actually the most up to date on SuDS devices in Scotland and provides a good insight on what can be achieved using SuDS devices.

However, this guidance includes weaknesses:

- Recommendations on the number of SuDS devices in series to use for different land use do not take into account which SuDS are used, their respective design and their place on the site; and,
- Selection matrices available do not take into account combined use of SuDS in series.

SuDS for roads (Working SuDS Party, 2009)

Within the context of recent legislation in Scotland, the Working SuDS Party has issued guidance for stakeholders involved in the design, maintenance and drainage of roads. This new guidance aims to remind each party of their duties towards the drainage of roads and promotes the use of SuDS techniques potentially applicable depending on the type of road developed. The document heavily promotes the use of a treatment trains and suggests that roads should be treated by at least two SuDS in series apart. The exception to this is roads in small residential development where only one SuDS element may considered as sufficient. Similar to The SuDS Manual (CIRIA, 2007), the recommendations do not take into account which SuDS are used and their respective design.

Supporting Guidance (WAT-SG-12)

This guidance supports the application of the Water Environment (Controlled Activities) (Scotland) Regulations (CAR) regulating runoff discharges controlled either by General Binding Rules or Licence. The purpose of the document is to provide background and context to the relevant GBRs and provide guidance on complying with the rules.

Regulatory Method (WAT-RM-08): Sustainable Urban Drainage Use

This guidance helps in determining whether a project is subject to the General Binding Rules or if an application to a license is necessary. The decision is made by a SEPA officer based on the assessment of land uses and development size evaluated in terms of number of car parking space/houses and the sensitivity of the receiving environment. This evaluation is largely based on the STTAT tool (Jefferies et al., 2009). Based on the results of the assessment, the project is either classified as low risk or high risk. In case the project is determined as low risk, no further consultation of SEPA by the developer or the local authority is necessary provided the project complies with the GBR (The Water Environment (Controlled Activities) (Scotland) 2011). If the project is considered as high risk, application to a licence is necessary. Application to a licence should be made by a responsible person who shall secure compliance with the terms of the licence. The license follows a consultation process to determine whether the proposed SuDS proposals are deemed sufficient or not. In parallel, the guidance encourages treatment train uptake by providing advice on the number of SuDS in series to implement to protect the receiving environment in regards to land use and project size. However, it should be noted that the guidance does not provide design recommendations apart from following design recommendations included in Sewers for Scotland 2 (2007) and concern only the design of regional controls. As a consequence, the design and extent of source controls is left to the appreciation of the local authority if the GBR only applies or to the local SEPA officer in the case of a licence. A summary on the level of SuDS to be used and whether a project is subject to GBR or licence is provided in Table 2-4.

	Number of houses / car park spaces				
Receiving Water Type	**<25**	**25-50**	**>50-100**	**100-1000**	**>1000**
Normal sensitivity watercourse	1 level	1 level	2 levels	2 levels	2 levels
Low sensitivity watercourse	1 level	1 level	1 level	2 levels	2 levels
Transitional waters	Minimal	Minimal	Minimal	Minimal	Section 4.5
Coastal waters	None	None	None	None	Section 4.5
GBR applies	*Standing planning advice* Local Authority checks source control design				
GBR applies	*SEPA provides site-specific planning advice* LA checks source control design				
GBR applies	*SEPA provides site-specific planning advice* LA checks source control design, Scottish Water checks pond/basin design if Sewers for Scotland 2				
Licence required	*SEPA provides site-specific planning advice* LA, Scottish Water, SEPA may check design				

Table 2-4 : SuDS requirement matrix (SEPA, 2006)

Sewers for Scotland, second edition (Scottish-Water, 2007)

This guidance, published by Scottish Water, aims to provide developers with technical standards for the construction of sewers network. The term sewer, in this latest version of the guidance, has been redefined to include SuDS components according to the WEWS Scotland act (2003). The document formalises the types of SuDS due to be adopted by Scottish Water provided they have been designed to their standard. The SuDS likely to be adopted are detention ponds, detention basins and underground storage.

2.3.3 WATER QUALITY DESIGN

The water quality requirement for the design of SuDS is based on the notion of water quality volume, corresponding to the volume either retained or infiltrated during inter-events. Consequently, only the SuDS including retention or infiltration techniques are taken into account in the evaluation of the water quality performances. The water quality volume is based on a multiple of the treatment volume defined on the experience gained at the Dunfermline Eastern Expansion project (DEX) presented in Section 2.2.4.

The treatment volume (Vt) for the DEX was computed using STORM (a hydrodynamic model) based on a four year analysis (1991-1994) for the DEX area (Roesner et al., 2001). On the hypothesis that the area would be developed with 67% of impervious areas, the capture of the first 12mm on the area considered would be sufficient to capture 90% of the storm events occurring. For the remaining 10% of rainfall events, it was thought that the capture of the 12 first mm of rainfall would capture the most polluted part of the rainfall occurring (first flush). This aspect is subject to discussion on the base of in situ measurement discussed in Section 2.1.1.2. Further computation undertaken with different urbanization scenarios has shown that the Vt volume necessary to capture 90% of the rainfall events was a function of the impermeability of the area considered (Equation 2-1).

$$Vt(m^3.ha^{-1}) = 90 + 45.I \qquad \text{(Equation 2-1)}$$

Where I is the fraction of imperviousness for the area considered (%).

The total treatment volume designed for detention basins, retention basins, wetlands and swales for the DEX area were based on a multiple of Vt varying from 1 for swales to 4 for wetlands and extended detention basins in order to have extended detention time and improve physico-chemical and biological removal of pollutants as detailed in Section 2.2.3.3. The DEX site had only limited constraints in terms of land take of the SuDS devices and construction of SuDS facilities were adopting the maximum design requirements proposed by the environmental regulator. No reduction of regional controls was proposed based on the water quality benefits achieved by source and site controls.

Following the experience gained on the DEX site, the Vt equation was then “improved” to take into account different soil and hydrological conditions (Equation 2-2). The basis for this change is not clear, a factor which has been the source of some concern (D’Arcy and Mclean, 2009):

$$Vt = 9 \times D \times \left(\frac{SOIL}{2} + \left(1 - \frac{SOIL}{2}\right) \times I\right) \qquad \text{(Equation 2-2)}$$

With:
D (mm) = M5.60 rainfall depth
SOIL = Soil classification (Flood Studies Report, 1975)

Following this early design of SuDS devices, research has been undertaken on the Vt multiple that should be used for the design of SuDS. A summary of design methods actually used in Scotland is provided in Table 2-5. There are clearly uncertainties on the multiple of Vt that should be used. The variety of land uses, catchment characteristics and the space requirements for SuDS are further increasing the complexity in adopting a clear rule for the multiple of Vt to be adopted. Despite recommendations regarding the volume to be adopted, the final decision is made by the environmental regulator officer based on expert judgement and taking into account land uses, catchment and socio economic situation for the site.

Source	Recommended permanent pool volume (based on Vt)
(CIRIA, 2000)	Permanent pool = 4Vt
(CIRIA, 2004)	Permanent pool= Vt (exceptionally = 4Vt). 4Vt should not be considered a baseline and appropriate criteria depend on level of pollutant removal required.
(CIRIA, 2007)	"However it has since been demonstrated that capture of 1 Vt will retain the majority of the pollution for treatment, and the treatment effectiveness of providing much greater volumes seems to be limited. It is still considered that sites with high pollution risks (due to high influent concentrations or high receiving water vulnerability) should be provided with additional treatment volume but the basis for the size increase has not been generally agreed. In this instance it is more important to provide a train of SUDS than just increasing the permanent pond volume."
(Scottish-Water, 2007)	Permanent pool = 1Vt for housing and up to 4Vt for non residential, industrial

Table 2-5 : Treatment requirements (Copty and Adshead, 2007)

2.3.4 WATER QUANTITY DESIGN

In addition to climate change impact due to increase expected rainwater volumes with more frequent, intense and longer events (Lu et al., 2001), the development of impermeable surfaces in urban and industrial catchments reduces the opportunity for rainwater to infiltrate into the soil. As a result, rainfall events are a source of high runoff volume that need to be discharged in the nearest receiving water bodies to reduce flooding risks on the catchment while mitigating adverse effects of increased peak flows and runoff volumes on receiving watercourses and downstream developments. The requirements of the different stakeholders regarding the management of runoff in terms of volume are variable, depending on the location considered and the likely impacts. The specifications regarding water quantity can be specified at different scales as follows:

The pipe network is generally designed to accommodate a 1 year return period event without surcharging and should be able to convey 30 year return periods without overflowing (Scottish-Water, 2007). For greater return periods (1-in-100 and 1-in-200 years), checks should be made to ensure no flooding occurs to properties. The design of the site layout or the drainage system should be modified where the required flood protection is not achieved. Greater protections might be required on request of the local authority if the development encompasses public buildings such as hospitals (Scottish Executive, 2004).

Downstream locations protection against flooding are ensured by attenuation of the runoff through the use of SuDS. The return period to be attenuated is usually taken between 30 and 200 years period depending on local authority requirement for flooding protection and environmental regulator requirement for environmental protection of the receiving water course. The discharges should be limited to the greenfield runoff rate for the corresponding return period calculated according to the methodology proposed in "Flood estimation for small catchments" (Mashall and Bayliss, 1994) for 1 and 30 years return period and any more extreme events in criteria specified by the local authority (Scottish-Water, 2007).

Although decisions made on the flooding defences can be facilitated by the use of models, either for the site (e.g. Infoworks, Section 2.5.2.2.1) or for the river (e.g. Mike 11, Hec-Ras). Decisions on the strategy to be adopted (construction of embankments, use of SuDS) remain a concerted decision of the environmental regulator and the local authority. This decision is further complicated by the choices that have to be made regarding the use of SuDS to attenuate different return periods.

2.3.5 CURRENT PRACTICE AND THE USE OF END-OF-PIPES

Despite the treatment train philosophy is largely encouraged by environmental regulators, the use of SuDS in series remains limited in Scotland with over 70% of the SuDS sites using only one SuDS device (Wild et al., 2002). Investigation of latest development plans of Scottish projects (e.g.: Clyde Gateway project in Glasgow (Copty and Adshead, 2007); South East Wedge Project in Edinburgh) demonstrate that predominant solution concerns the use of regional controls allowing the treatment of the whole site considered. This approach is commonly known as "end-of-pipe". The reasons leading to the use of "end-of-pipe" solutions rather than the use of treatment trains solutions are investigated in Chapter 3.

2.4 CURRENT SUDS DESIGN ELSEWHERE

SuDS are also commonly used in other countries. this section summarises design requirement for key countries supporting SuDS implementation.

2.4.1 ENGLAND AND WALES

SUDS, due to be adopted by local authorities, are designed to provide attenuation by restricting runoff rate of events up to a 100 year return period to the greenfield runoff rate. More stringent limitations can be taken by local authorities in accordance with the environmental regulator by limiting the discharge rate to a maximum of 2 l/s/ha. Legislation currently under review (Defra, 2011) requires minimum treatment to runoff before discharging it to the receiving water body. The level of treatment to be provided is decided as a function of the source of the runoff and the sensitivity of the water body in an approach similar to the STTAT tool (Jeffries, 2006) detailed in Section 2.5.1.

2.4.2 FRANCE

The design objectives to be achieved for SuDS are set out regionally by the environmental regulator. They commonly focus on limiting the discharge rate of a 100 year return event to a given flow rate determined based on expert guidance. There are no requirements from the environmental regulator regarding runoff treatment before discharging to the receiving watercourse. However, concerns raised by local authorities regarding improvements of watercourses have led, in some cases, to the implementation of permanent pools in ponds to provide water treatment.

2.4.3 AUSTRALIA

Water quantity design requires for virtually all developments to limit discharges to the pre development rates. Water quality objectives are defined at the local or regional scale based upon the receiving waterbody's state and any water quality objectives. Virtually all SuDS combinations may be used provided that demonstration of compliance with water quality objectives is achieved (Government of Western Australia - Department of Water, 2006).

2.5 DECISION SUPPORT

2.5.1 INTEGRATED TOOLS

Different land uses, site and catchment characteristics lead to very different situations where water quality and quantity objectives can be quite different following the requirement to protect downstream locations from flooding. The final decision maker (environmental regulator and local authorities) should make a decision to implement SuDS so as to give an appropriate response to water quality and quantity issues. Despite regulations and guidance, these decisions makers still have some freedom in implementing SuDS. In order to help decision makers to reach the best solution, several decisional tools exists and the Section below aims to present some of them.

SUSTAIN (USEPA, 2010)

SUSTAIN is a tool developed by USEPA which is being trialled at the time of writing. SUSTAIN is a software tool which works in parallel with a GIS database (Arc-Gis). Based on possible SuDS implementation for the area, the model performs hydrological, quality and costs estimates for the different SUDS combinations available. The optimum solution for the area is then determined as a function of the pollutant removal target achievable within minimum costs. Water quality, hydrological modelling and costs determination are largely based on existing work:

- Runoff generation and routing are based on storm water management model (SWMM) algorithms taking into account potential evapo-transpiration and infiltration to determine runoff characteristics.
- Pollutant load generation uses build up and wash off processes adapted from SWMM.
- BMP performances are similar to the ones described for model for urban stormwater improvement conceptualisation (MUSIC) and assume pollutants will be removed following the first order decay kinetics while hydraulic performance is modelled using continuous stirred tank reactor (CSTR) in series.
- Cost determinations are based on a limited amount of data made available from wholesale or retail companies.

Despite the fact that SUSTAIN is able to cope with SuDS in series and thereby allows the characterization of the treatment trains and eventual comparisons to be made, several concerns exist:

- The economic evaluation is limited to capital costs and does not take maintenance costs into account.
- There is no consideration of the land take for the different SUDS options.

Kellagher (Kellagher, 2008)

The sustainability assessment tool developed by Kehallgher is a water quality assessment tool coupled with a hydraulic performance assessment tool. The water quality tool is based on the expected pollutants for different surfaces, sensitivity of the receiving waters and expected SuDS performances. Default values are provided but can be user modified; the score obtained by the SuDS treatment train should offset combined values of expected pollutant loads and receiving water sensitivity. The hydraulic tool assesses the performance of the drainage system against the greenfield behaviour of the site for frequent and extreme events. A performance indicator is calculated and the extent to which runoff is attenuated. A key benefit of the tool is that it is taking into account performances of SuDS in series despite the fact that the location and the extent to which the SuDS are used is not taken into account. However, this tool is only looking at water quality and quantity performances with no account on potential amenity and biodiversity objectives. Main criticism regarding this tool would be that no explanations on how the default scores are attributed are given.

STTAT tool (Jefferies, 2006)

The Stormwater Treatment Train Assessment Tool (STTAT) is a water quality tool developed to support SEPA policy. The STTAT tool is a scoring system which may be used to assess the risk presented by the land use and to the receiving water body. The sum of the scores obtained should be at least equalled by a score for the treatment train. Hence, the scoring system presents a good opportunity to:

- Determine the number of SuDS devices that should be used and satisfy SEPA environmental criterions.
- Take into account the treatment efficiency of the SuDS devices by allocating them a different score (an underground storage, recognized by SEPA to have a very poor efficiency in terms of water quality, is scoring 10 whereas a swale is scoring 25).

Although the method is simple and easy to use, two weaknesses are clear:

- Similar to Kellagher, there is no details available on the basis of the scores;
- The other aspects of the drainage, and especially water quantity management, amenity and biodiversity potential are not taken into account despite these being key SUDS objectives.

Swan (Swan, 2002)

A framework for selecting SuDS devices for retrofitting to different land uses, catchment and site characteristics has been developed by Swan (Swan, 2002) and subsequently improved (SNIFFER, 2006). Based on site and land use characteristics, the presented framework allows selecting the best SuDS retrofitting action base on its easiness to be retrofitted and its efficiency to reduce water quantity. The presented framework addresses retrofitting issues for both separate and combined systems and can thus address intermittent CSO discharge issues and has been applied to several case studies. However, the work, by focussing only on the reduction of CSO discharge, pays little attention to the quality of the surface water either discharged or infiltrated into the soil. Moreover, consideration of water quantity only removes interest in using a treatment train.

Daywater project (Thevenot, 2008)

The DayWater project has been developed within the European region and is composed of a multi-criteria comparison tool. This tool allows the comparison and assessment of SuDS devices using a wide range of criteria: technical, environmental, operation and maintenance, social and urban community benefits, Economic and Legal and Urban Planning. For all these criteria, indicators have been developed and values proposed for criteria appropriate to SuDS devices can be applied. For criteria depending on the area considered, values should be chosen by the user. The different SuDS devices are then ranked using a weighting system. This system presents a holistic approach and in doing so integrates the interests of the different stakeholders involved in the planning of SuDS devices. However, this approach takes into account only one SuDS device at a time and does not consider the treatment train. Moreover, the approach is based on ranking and corresponding values are not given (e.g. costs) which may influence user perception.

2.5.2 SUDS MODELLING

The previous sections made the link between the potential impacts of urbanisation on the water cycle and how these can be managed using SuDS devices and in particular with the use of treatment trains. Ongoing research to characterise SuDS performance and optimise implementation of SuDS encompasses technical and societal issues using both qualitative and quantitative methods. The Section below provides an overview of current research conducted on SuDS and, in particular, focuses on the hydrological and pollutants removal performance and how these are modelled. Research conducted on the potential for SuDS to provide amenity and biodiversity, costs implications and planning research is also considered.

2.5.2.1 Water quality modelling

Water quality requirements normally focus on capturing a given volume of runoff for treatment via infiltration or detention in permanent pools. Despite uncertainty associated with water quality improvements achievable by SuDS (Centre for watershed protection, 2007), refined analysis of pollutant removal behaviour has shown that specific trends can be identified. Statistically significant correlations between pollutant concentration (TSS, TP, TN and heavy metals) entering and leaving SUDS systems (filters, swales, detention and retention basins) have been established and related to design characteristics (Barrett, 2008). These correlations have influenced SuDS specific design characteristics such as slopes, vegetation density and height in swales (Deletic and Fletcher, 2006; Barrett et al., 1998; Schutes, 2001); pond volumes (Wu et al., 1996; Pettersson and Lavieille, 2006), vegetation coverage in wetlands (Kadlec, 2008) and the impact of filter material and pore size for pervious pavement (Gilbert and Clausen, 2006).

These investigations have paved the way for the development of numerous individual SuDS water quality models which take SuDS specific design characteristics into account. These models can be based on theoretical calculations (e.g. sedimentation equation) and/or empirical relationships. For example, researchers (Morgan, 2007; Larm, 2005; Mourad et al., 2005) have developed models for modelling ponds and basins. Others (Deletic and Fletcher, 2006) have developed models for swales and filter strips. It should be noted that most of these models have usually been developed on the calibration of a limited number of site specific SuDS devices and are based on raw runoff. Consequently, the ability for some of the models to be transposed to other sites or using different runoff composition is not clear. Although the models developed for individual SuDS in their context are accurate and reliable, their ability to estimate the benefits of several SuDS in series is less clear.

In order to estimate the water quality benefits obtained from SUDS deployment, models which can be used to represent a wide range of different SUDS have been developed. These models are often used to support Total Maximum Daily Loads (TMDL) regulations in the US or Australia. Some of the well-known water quality models used by engineers and consultants around the world for water quality modelling purposes are summarised below in the remainder of this section. These models have been summarised in Elliott and Trowsdale (2007) who identified ten suitable software for SuDS modelling. However, amongst the water quality models identified and presented, only MUSIC, SWMM and Infoworks CS out of the ten models presented have been identified as suitable to model the whole range of SuDS available. Summary of the functioning of these three software are given below.

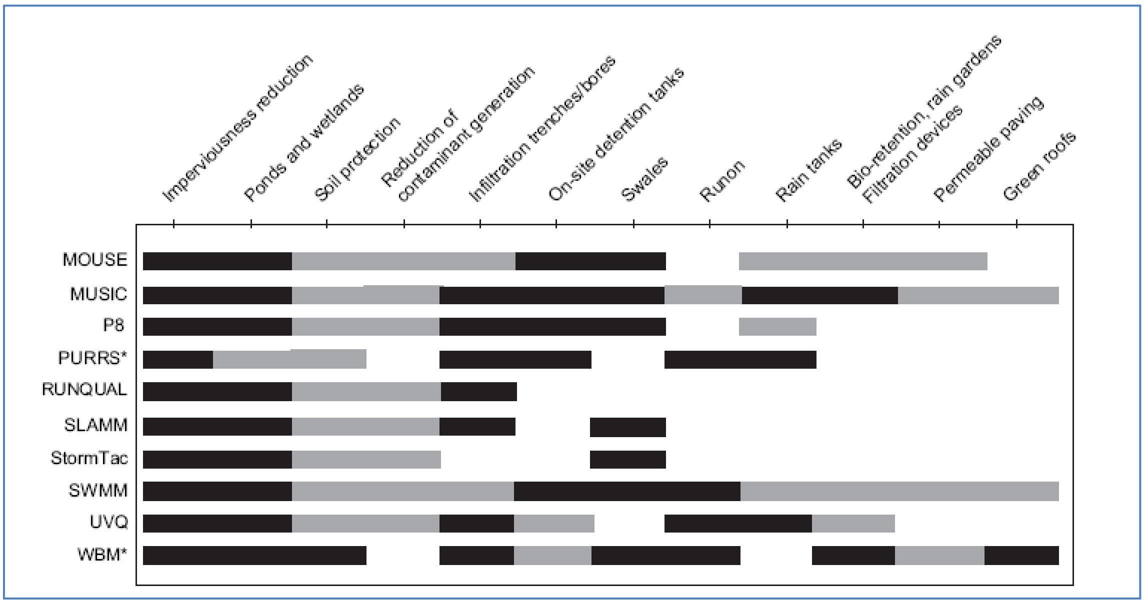


Figure 2-6: Review of water quality models. Grey shading indicates that the model does not explicitly address the device, but could be used to model the device. Model with an asterisk do not address water quality (Elliott and Trowsdale, 2007).

MUSIC model includes theoretical water removal efficiencies for TSS, TP and TN using the first order decay kinetic described by (Kadlec and Knight, 1996). Removal efficiencies are either based on the sedimentation equation defined by Fair and Geyer (1954) or calibration based on experimental fieldwork (Wong et al., 2006).

Infoworks CS is a hydraulic model coupled with a water quality model. Build-up and wash off processes for a range of pollutants (TSS, TKN, NH4, TP) and physico-chemical indicators (BOD, COD) are modelled by defaults based on calibration. Modelling of SuDS is achieved using treatment nodes in the network where removal equations should be defined by the user for each node. Infoworks is the main hydraulic model used in this thesis and its functioning is detailed in the Section 2.5.2.2.1 for the hydraulic part.

SWMM is a common water quality model used in the US. It is also a hydraulic model coupled with a water quality model where treatment is applied to nodes following removal equations defined by the user.

Overall, Infoworks CS and SWMM are very similar in the sense that the user should specify pollutant removal equations in the model based on site specific data. Unless preliminary data allow calibrating the model for build up, wash-off and pollutant removal in SuDS, it is difficult to apply these techniques at a design stage to estimate SuDS benefits of a treatment train. Contrary to this, MUSIC provides default values based on calibration studies (which can be modified by the user if necessary) and hence is arguably more suitable to model hypothetical or conceptual SuDS treatment trains. For this project, MUSIC licence is granted by the CRC and is used for the assessment of treatment trains even if other software (e.g. Infoworks CS or SWMM) could have produced comparable results provided calibration data are provided. Details on how MUSIC is functioning are given in Section 2.5.2.1.1.

2.5.2.1.1 Model for Urban Stormwater Improvement Conceptualisation (MUSIC)

MUSIC, developed by eWater Cooperative Research Centre, is a simplified hydrological and hydraulic model coupled with a water quality model based on the first order decay kinetics. Based on its ability to model a wide range SuDS device and the relatively modest requirements for calibrating the system, MUSIC is chosen as the main water quality package for the purposes of this thesis.

Hydrological model – rainfall runoff generation and routing

The runoff generation in MUSIC is based on a simplified model (Chiew and McMahon, 1997). The user interface allows the user to set up pervious area and groundwater properties by specifying initial infiltration rate, initial moisture conditions of the soil and base flow rate based on an eventual calibration of the process. Rainfall runoff and base flows are then calculated at each time step based on the parameters of the model and the rainfall hyetograph.

Hydraulical model – SuDS modelling

The hydraulic performances of the different SuDS are modelled by a series of well mixed water bodies or Continuously Stirred Tank Reactors (CSTRs). The number of

CSTRs is related to the hydraulic efficiency (λ) defined as follows (Persson et al., 1999):

$$\lambda \approx \frac{1}{N_{CSTR}}$$ (Equation 2-4)

With:
λ: Hydraulic efficiency
N_{CSTR}: Number of CSTR

Water quality model

The water quality performance is modelled using first order kinetics (Equation 2-5) observed in SuDS monitoring studies (Ackerman et al, 2008; Wong et al., 2001).

$$q\frac{dC}{dx} = -k(C - C^*)$$ (Equation 2-5)

Where:
q: hydraulic loading rate (m/y)
x: fraction of distance from inlet to outlet
C: concentration of the water quality parameter
C*: background concentration of the water quality parameter
k: decay rate constant

MUSIC assumes TSS, TP and TN follow standard particle size distribution initially measured for the Brisbane area (Australia) and the removal of pollutants mainly occurs through primary processes, sedimentation and filtration. The sedimentation equation in basins being dependent upon particle density, using Stokes law and Rubey's equation allows settling velocity for different particle size to be approximated. Thus, removal by particle settling in basins can be approximated depending on retention time. For filtration devices (swales), calibration of k and C* values have been undertaken based on observed performance (Wong et al., 2001; Wong et al., 2006).

This SuDS modelling approach allows MUSIC to take into account most of the parameters influencing SuDS performance:

- The size of the SuDS (ponds, basins or swales) is taken into account by the hydraulic loading in the equation, corresponding to the incoming flow divided by the area of the facility.
- The time of retention in the SuDS is represented by using the associated hydraulic model.
- The vegetation height is considered by allowing the water to bypass the system during high flows, thus modelling high flows in swales.
- The application of the first order kinetics removal theory takes into account the different SuDS performance for different pollutant input.
- The variability in pollutant load is taken into account by the model by varying inputs stochastically within user defined boundaries (the default value corresponds to 67% of the standard deviation observed for the Brisbane area).

However, the use of MUSIC is based on a key assumption that may affect modelled SuDS performance. The main criticism that can be formulated is that the pollutant removal modelling in MUSIC is largely based on the key assumption that pollutants are in solid form. The solids are represented as different particles size with each having its own sedimentation and infiltration characteristics. Thus particle size distribution (PSD) is a key factor in the pollutant removal predictions. However, using MUSIC and the default k and C* values supposes that default PSD is used. This default PSD is based on measurements undertaken in both Brisbane and Melbourne catchments. Surveys conducted by Sartor et al. (Sartor et al., 1974) have shown that PSD can vary from a catchment to another, with geology of the site deemed as being the main influencing factor. Although using PSD specific to the site would be more accurate, this data would require significant monitoring of the site and is not likely to be possible in many cases. As it is difficult to assess initial PSD, it is also difficult to assess it after treatment by SuDS. It is likely that the SuDS will remove a larger percentage of gross particles (Deletic, 2005). Thus, PSD should ideally be recalculated after each SuDS element in the treatment train. However, this task would be time consuming and unrealistic given uncertainties associated with the recalculation.

2.5.2.2 Hydraulic modelling

As SuDS are used to remediate to excessive discharges, peak flows and volumes in rivers, research is underway to understand their hydraulic potential. From hydraulic models developed initially for the water industry piped systems, SuDS modelling has progressively improved (e.g. and amongst several others (Lebeau and Konrad, 2009; Pagotto et al., 2000)). This section aims to review current hydraulic modelling tools incorporating features for SuDS modelling.

SWMM is a well established hydraulic and water quality modelling package in the US where modelling of manholes and pipe networks is done through the modelling of a series of nodes and links having different hydraulic and water quality improvement properties. Apart from storage properties, SWMM provides very little opportunity to model the hydraulic performance of SuDS.

Infoworks CS is a well established hydraulic and water quality modelling package in the UK. The modelling of manholes and pipe networks is undertaken through the modelling of a series of nodes and links respectively having hydraulic and water quality properties. Newer versions of Infoworks include facilities to model specific SuDS drainage devices.

Micro-Drainage is a set of different dependant modules which may be used to design and simulate pipe networks. The latest version of Micro-Drainage includes a module (Source Control) for the modelling and design of the whole range of SuDS devices.

Due to costs constraints, easiness and prior detailed knowledge of the product, Infoworks CS has been used for this project as the default hydrologic package. Although this software is a well established package in the UK, any other hydraulic package such as SWMM or Micro-Drainage would function on similar principles and could also be adapted for use in this research. The Section 2.5.2.2.1 provides an overview of the main mechanisms used in the modelling of catchment hydrology using Infoworks CS.

2.5.2.2.1 Infoworks CS

Infoworks CS, developed by Wallingford, is the hydraulic package used for the presented research. The software integrates four main modules for rainfall, runoff and sewer routing and SuDS modelling as detailed in the section below.

Rainfall

Infoworks CS presents the opportunity to either generate hyetographs using the FEH methodology based on geographical location or rainfall data directly. This choice allows the software to be used to either simulate the network using times series rainfall (TSR) from past rainfall events or use design rainfall for the design of SuDS solutions.

Runoff generation and surface routing

The system inflow hydrograph is derived from the hyetograph by taking into account the initial losses and overland runoff routing on the catchment surface. The software allows the catchment to be divided into a number of surface types, the main ones which generate runoff being roads, roofs and pervious surfaces. These surfaces are associated with eventual losses (initial and/or continuing) that can occur. Initial losses can be modelled as absolute, depending on the slope or using soil catchment characteristics. Continuing losses are represented using infiltration models. The runoff is then routed using one of the three routing equations available.

Sewer routing

Pipe network in Infoworks is represented by a series of links and nodes which generally correspond to pipes (or swales) and manholes (or ponds) respectively. The flow is routed using Barré de Saint-Venant equations.

SuDS modelling

The SuDS characteristics may then be modelled as follow:

- Filtration techniques can be modelled by the modification of the flow equations and taking permeability and porosity into account (e.g. trench).
- Infiltration can be modelled for nodes (ponds and basins) and links (swales) by allocating infiltration coefficients.
- Attenuation is modelled through the modelling of storage structures for nodes.
- Conveyance networks (swales) are modelled by modifying roughness coefficients and cross-sections of links.

2.5.3 *Whole life costs determination*

The development of SuDS devices has often been perceived by stakeholders as higher than those of conventional drainage (McKissock et al., 1999). Beyond construction costs, the adoption and the associated management of systems supporting vegetation and biodiversity in some cases has been associated with high maintenance requirements. For this reason, costs have been reported as the main barriers to SuDS implementation in Scotland (McKissock et al., 2003). Literature reviewed related to the determination of costs for maintenance shows that two methodologies can be used. The first methodology is based on data collection relating to existing SuDS installations whilst the second is based on estimates derived via bills of quantities.

Method 1: Costs observations

Numerous SuDS projects have been developed worldwide and some research projects have or are collecting data from stakeholders involved in the construction or the maintenance activities (bmpdatabase, 2010). Based on the economic data collected, relationship between main design parameter and costs can be established provided sufficient data have been collected to allow a statistical interpretation. For example, costs-size relationship for ponds has been established by Brown (Brown and Schueler, 1997) based on construction costs of 41 SuDS ponds. Similarly, based on an up-to-date review of published costs, Weiss (Weiss et al., 2007) established relationship between water quality volume, defined as the volume of water being treated by the device, and construction costs for basins, infiltration trenches, bioretention and sand filters. This method has been used in MUSIC to determine whole life costs of SuDS treatment trains: the whole life cost estimation is based on cost-size information for structural stormwater quality BMPs reported in (Taylor, 2005) and is actually under review to produce a cost unit approach supported by statistical references (Ira et al., 2008). This approach presents several difficulties as follow:

- Collecting costs data from companies is usually a sensitive subject as this data is kept confidential for competition purposes. Consequently, the amount of data collected for SuDS and published in the public domain is very limited. However, some data is available - for example, the cost estimates of pervious pavement (Taylor, 2005).
- SuDS design can be very site specific. Costs can vary considerably due to local conditions (e.g. need for retaining wall) or regulatory requirements (e.g. fencing) (Weiss et al., 2007).
- Maintenance activities may be part of larger landscaping projects, making it difficult to establish the costs associated specifically with the SuDS devices (Clemie, 2006).

- Consequently, estimates of whole life cost using observations has sometimes been combined with bill of quantities estimates or broad approximation of maintenance costs (Weiss et al., 2007).

Due to these issues, there is significant uncertainty associated with the analysis and forecasting of whole life costs for SuDS. Estimation of costs for a case study reported variations 1 to 4 times for a wetland and 1 to 3.6 times for an extended detention basin with a 67% confidence interval (Weiss et al., 2007). However, it is likely that data on SuDS costs will improve in the future due to the data collection currently underway (bmpdatabase, 2010). This will provide opportunity for refinement of the costs estimates and a sufficient number of reported projects will allow taking site specific details into account.

Method 2: Bill of quantities

Based on published civil engineering costs (Langdon, 2009), the bill of quantities approach is based on unit costs of labour and material for civil and structure engineering works. The unit costs provided have been used by several authors to reach quick estimates of SuDS costs, including construction and maintenance costs over several years (Stovin and Swan, 2007; Duffy et al., 2008). Based on this technique, a specific methodology has been developed by UKWIR to determine the costs of construction and maintenance over 50 years for SuDS devices such as detention basins, permeable pavement, retention basins, filter drains and swales for the UK and the USA (Ellis and Aftias, 2008). The technique has the advantage of providing a framework to estimate costs and maintenance over a specified period and take into account site specific details.

2.6 DISCUSSION

This section has underlined how SuDS devices can help in mitigating adverse effects of urbanization and industrialization on the water cycle while satisfying biodiversity and amenity objectives. Despite strong encouragement to use SuDS in treatment trains (CIRIA, 2007; Working SuDS Party, 2009) and recent evidence on the achievable benefits (Heal et al., 2006; Heal et al., 2009), the use of SuDS in series remains limited in Scotland with over 70% of the SuDS sites using only one SuDS device (Wild et al., 2002). Whilst progress has been made recently by making the use of SuDS mandatory for virtually all new developments built after the 1st of April 2007, new developers prefer end-of-pipe SuDS while surface drainage in developments built before the legislation will not use SuDS.

Recent changes in drainage habits have allowed water quality improvements and better management of water volume. Although these efforts should be acknowledged, a step change is now required to place urban drainage a step closer to sustainability by:

- using treatment trains;
- integrating SuDS for all development types with separate systems built before or after the legislation came into force.

Understanding the barriers to the implementation of SuDS treatment trains along with the development of benchmarks representative of the potential benefits is key to their increased use.

Chapter 3 - Methodology

3.1 Critical review of current SuDS schemes

The literature review presented in Chapter 2 highlighted how SuDS schemes are implemented in Scotland. In comparison with other drainage techniques outlined in Chapter 1, the implementation of SuDS techniques has allowed significant benefits to be delivered. In particular, end-of-pipe solutions implemented for large developments allowed water quality improvements and flood protection to be made despite low level of amenity and biodiversity were achieved. However, the results achieved should be seen as limited in comparison with potential benefits associated with treatment trains. As shown in Chapter 2, the use of treatment trains allow further benefits in terms of water quality, flood prevention and amenity/biodiversity to be achieved. Although the use of a treatment train has been made compulsory for virtually all development types over 50 houses/car park space as for industrial areas, the extent and types of SuDS to be used upstream of the regional control are unclear and left to SEPA officers' approval (SEPA, 2006).

Hence, while end-of pipe solutions have allowed significant benefits to be made, a move towards the use of treatment trains is desirable for large developments, industrial areas and retail parks with the potential for degradation of water quality and the hydraulic regime.

Key to establishing a framework to support the implementation of SuDS treatment trains is understanding the context in terms of barriers and drivers. To support this activity, targeted interviews with key stakeholders involved in SuDS implementation were undertaken. These interviews allowed the identification of the barriers to and the drivers for the implementation of SuDS specific to each stakeholder category in the context of current guidance and legislation. Identification of barriers to and drivers for the implementation of SuDS may then be placed within the context of current knowledge and how they will be assessed by key stakeholders at the design stage.

The following stakeholders have been considered:

- Local authorities: S. Gillon (Glasgow City Council) and G. Mather (Midlothian City Council)
- Consultancy: H. Adshead (Hyder Consulting Limited)

- Sewerage undertaker: A. McMillan (Scottish-Water)
- Environmental regulator: B. D'Arcy (SEPA) and S.Pallant (SEPA)
- Residents: a survey has been undertaken to fully understand what were the expectations, and potential concerns, of the residents living in close proximity to SuDS devices. The results of this survey are presented in Chapter 4.

These key stakeholders have been considered as a sufficient sample of those regularly involved in drainage issues generally and in SuDS implementation specifically to provide general views on the drivers and barriers associated with SuDS implementation. The structured interviews, supported by the available literature on the subject (Todorovic et al., 2008a; McKissock et al., 2003; White and Alarcon, 2009; Schafer et al., 2006; Todorovic et al., 2008b; Brown, 2005; Brown and Farrelly, 2009; Farrelly, 2008; White and Howe, 2005) have allowed the identification of technical, social and institutional barriers and drivers in Scotland and elsewhere. These reviews and the associated interviews have underlined that the non implementation of SuDS devices, especially source and site controls, was primarily due to socio-institutional barriers rather than technical challenges (Schafer et al., 2006). Contrastingly, in Scotland the lack of guidance and experience in the past has acted as a barrier to SuDS implementation far beyond other socio-institutional issues (McKissock et al., 2003). This is a situation which has been superseded with the publication of appropriate guidance and moves to share good practice (CIRIA, 2007; Working SuDS Party, 2009; Scottish-Water, 2007). Consequently, the technical barriers for SuDS implementation will not be considered further and only the socio-economical issues are considered as preventing SuDS uptake in Scotland. The main socio-institutional barriers reported in the literature and in the interviews are listed in this section:

Land take: The land occupied by SuDS can be seen as a major issue by developers and local authorities. This is especially the case where land value is high (Valuation Office Agency, 2010a; Valuation Office Agency, 2010b), and in this case developers and local authorities will seek to maximise the potential development to optimise their return on investment. The implementations of SuDS, especially large facilities such as ponds or wetlands, are seen as a drawback especially in high density developments where land is valuable. The perception of land loss due to SuDS implementation is reinforced where drainage conditions constrain the implementation of SuDS to a limited zone.

Adoption: If the system is not adopted by the sewer undertaker, Scottish Water, the responsibilities and the extra costs associated with the adoption of SuDS systems are a significant drawback for developers, local authorities, private owners and road authorities. This situation has largely prevented SuDS types other than those adopted by Scottish Water from being implemented.

Construction and Maintenance costs:
In contrast to hard engineering systems, SuDS are generally perceived as having high maintenance needs (Taylor and Wong, 2002) and this is particularly true where SuDS devices have a high amenity value (Barrett, 2004). Depending on local agreements, the costs associated with the construction and maintenance of SuDS devices, unless Scottish Water adopts the SuDS, are to be paid by local authorities, road authorities, land-owners (private) or developers. Thus, the building of the SuDS devices within curtilage is considered as an additional cost where the alternative is a direct discharge to Scottish Water owned pipe systems. Despite the potential amenity-biodiversity improvements to the area, these extra costs are often not considered as providing sufficient additional benefits to the owner to be implemented. This is particularly true with a culture where water charges are unaffected and do not offer potential payback to the owner for following best practice.

Safety: The presence of open water bodies such as ponds and wetlands has sometimes been perceived as a major risk by residents living in close proximity. The fear of drowning, especially where children are at risk, is reported as a major drawback by residents living in close proximity of some ponds (Apostolaki and Jefferies, 2005).

The non-integrated approach: The high number of stakeholders involved in drainage provision can make the application of innovative solutions difficult. As drainage is not necessarily the main stakeholder concern, organising common meeting to consider it in detail may be difficult (Adshead, 2006).

Similarly, the drivers for SuDS implementation were identified. These drivers were primarily implemented to offset the adverse effect of urbanisation (presented in Section 2.1) and are supported by regulatory requirements. Secondary objectives were to provide amenity and biodiversity according to the SuDS triangle philosophy. SuDS drivers are summarised in the remainder of this section.

Water body protection: the protection of water bodies, including rivers and groundwater, is the main focus of the environmental regulator in its duty to protect natural resources whilst promoting sustainable development (European Communities, 2000; HMSO, 2005). With respect to SuDS, the environmental regulator seeks to maximise the removal of pollutants carried by the runoff before the water is either discharged into local water courses or infiltrated into the underlying soil. This is enforced through SEPA's requirement for SuDS under GBR10 and GBR11 enforcement (Section 2.3.2).

Flood protection: the management of water quantity is a concern for local authorities and the environmental regulator in their duties to protect properties from flooding (Scottish Executive, 2004; SEPA, 1998b). The requirement for flow attenuation to mitigate downstream flooding can be offset by the use of SuDS to reduce the scale of hard engineering options such as storage and embankments. This includes the regulation of runoff rates where the environment is particularly sensitive to flow changes (Scottish Executive, 2004).

Amenity: The amenity provided by SuDS has been perceived as a potential "bonus" (Apostolaki and Jefferies, 2005). The additional attractiveness of the area achieved by SuDS and its potential to make living there more desirable has been used as a key incentive by SEPA to promote the use of SuDS with local authorities and developers (SEPA, 1998a; SEPA, 2000).

Biodiversity: Biodiversity is threatened by:

1) urban activities with generate pollutants (Section 2.1), and;

2) the impact of climate change (Pearson et al., 2002; Walther et al., 2002).

Despite the uncertainties regarding the potential impact of climate change, worldwide species extinction is expected (between 15% and 37% by 2050 for some regions (Thomas et al., 2004)). In its duty to protect biodiversity (HMSO, 2004), the UK have setup a biodiversity action plan with the aim of protecting biodiversity in the UK (UK Biodiversity partnership, 2007). The UK biodiversity action plan aims at developing a common strategy for UK countries in establishing a common ground for guidance and policies. SEPA, appointed as the environmental regulator, is in charge of applying UK biodiversity action plans in Scotland and thus protect and improve biodiversity.

Independently of the consideration of specific issues, the presence of SuDS can help in safeguarding biodiversity in the receiving waterbodies as well as providing wildlife/biodiversity in cities by providing greenspaces.

3.2 RESEARCH HYPOTHESIS

The structured interviews have underlined that the drivers for the implementation of SuDS were numerous and concern all the categories of stakeholders. Considering these drivers, it is clear that the implementation of treatment trains would consistently maximise the benefits associated with the use of SuDS techniques. In particular, the benefits achieved in terms of water quality, as outlined in Chapter 2, are consistent with the objectives of achieving good ecological and chemical status for the water bodies while increasing the potential for amenity and biodiversity in cities. However, at first sight, these benefits should be put back in the context of their potential impact on other stakeholder's concerns such as land take and the costs associated with SuDS deployment at source and site controls.

The underlying hypothesis of the presented research is that benefits associated with SuDS treatment trains compensate for their potential drawbacks. Consequently, potential changes in SuDS implementation schemes are sufficient to move towards a wider uptake of SuDS, especially source and site controls. In the context of the current SuDS implementation scheme, it is suggested that the following changes are necessary to favour treatment train deployment:

- Changes in the way water quality is estimated: current implementation strategy relies on the notional captured volume (Vt) estimation. While the captured volume gives a satisfying insight of the potential treatment achieved for SuDS including a retention volume, no consideration is given to other SuDS despite the knowledge of their potential to remove pollutants from urban runoff.
- Changes in the way SuDS are adopted: due to the potential for devices such as ponds designed to Scottish Water standards to be adopted, current schemes favour the deployment of SuDS as regional controls. In this situation, there are no incentives for the deployment of source and site controls. In this context, changes in adoption schemes are set by the regulatory framework.
- Changes in how SuDS are valued: although current research has shown SuDS with high amenity and biodiversity potential are valued by residents living in

close proximity, this potential is seldom taken into account by developers. It is hypothesised that the potential amenity delivered by SuDS could potentially help to increase the attractiveness of the development and partially offset the costs associated with their construction and maintenance.

In order to test this hypothesis, it is proposed to undertake a holistic comparison of competing potential SuDS treatment trains. The proposed holistic comparison is a three step process detailed as follows:

- The first phase focus on identifying the potential SuDS that could be implemented based on available data regarding land use, catchment and other site considerations.
- In the second phase, the SuDS selected are assembled in treatment trains. This step is at the core of the methodology and focuses on selected benchmarks for drainage solution performance: water quality performance, whole life cost, land take for different pollutants and resilience in dealing with flows resulting from a range of design storm return periods. The selected benchmark indicators are selected based on the perceived objectives and barriers of the different stakeholders.
- The third and last step is to analyze the results and determine whether the changes in adoption scheme, water quality evaluation and integrated approach are sufficient to enforce SuDS treatment trains whilst protecting water resources and population against flooding within the context of acceptable costs and land take.

3.3 METHODOLOGY DEVELOPMENT

3.3.1 DATA AVAILABILITY AND SUDS PRE-SELECTION (PHASE 1)

The holistic assessment of SuDS can only be achieved once potential SuDS solutions have been identified. Two sites where SuDS are likely to be implemented were selected to allow an appraisal of the tools developed in this thesis. The Dalmarnock Road area is used to develop greenfield and brownfield cases studies whilst the Houston Industrial Estate area is used as a retrofit case study. Although both these sites are introduced in detail in subsequent chapters, a brief overview is provided here to facilitate the development of the methodology.

For the **Dalmarnock Road area,** a residential development project, only very broad development plans for the area were available. It is likely that further development plans will be issued in the future and these might restrict the initial hypothesis made regarding SuDS implementation. The plans used to develop the methodology suggested that the site will be completely redeveloped. The proposed development densities were adopted as the starting point for the choice of SuDS to be considered in the holistic assessment. For the purposes of this study, two development scenarios were considered for the Dalmarnock Road site:

- Realistic – Brownfield
- Theoretical - Greenfield

Brownfield development assumes past development will result in soil contamination and, as a result, restraint the use of SuDS under certain conditions. In both cases, where needed, the surface drainage system was based on information provided by the development plans and by following best design practice (Scottish-Water, 2006). With regard to the reported pollution and recent flooding events, the challenge at this site for this project is to propose a performing drainage system to treat and attenuate the runoff to a high standard. However, the potential land take of regional control devices has been reported as a major drawback by key stakeholders and had to be minimised in order to increase the potential available development for the area.

This approach was in contrast with the approach developed for the second case study: the **Houston Industrial Estate.** Houston Industrial Estate is an existing development with a separate system where there is a need for SuDS retrofitting due to the impact runoff from the site is having on an adjacent watercourse despite existing regional control facility (D'Arcy et al., 2007). The fact that the site already exists in a viable form impacts greatly on the approach adopted. A visit to the site undertaken in January 2010 in conjunction with a review of research undertaken by other authors (SNIFFER, 2006; Heal et al., 2004) and network data provided by Scottish Water allowed the identification of the SuDS devices which could potentially be retrofitted for the area. With regard to device selection, the challenge at this site for this project is the implementation of source and site controls within reasonable budget and land take to complement the existing regional control in terms of water treatment and attenuation.

Despite availability of guidance and decision making help regarding SuDS implementation for different development types (Section 2.5), device selection is still not straightforward. The selection of the SuDS likely to be implemented is very different from a site to another and is the result of site, catchment and land use characteristics. The details and the knowledge of these characteristics are very different from a site-to-site and are likely to evolve with time. Thus, the selection of SuDS at a greenfield site allows the consideration of a wide range of SuDS, whilst the brownfield or retrofitted areas have constraints which limit SuDS uptake. Thus, the SuDS selection is not issued from a straightforward process but is rather derived from catchment, site and land use constraints known at the time of investigation.

3.3.2 HOLISTIC ASSESSMENT OF SUDS SOLUTIONS (PHASE 2)

The assessment of the solutions derived from the first phase is at the heart of the presented methodology. Key to the assessment is the establishment of benchmarks reflecting stakeholders' interests in regards to the identified barriers and drivers and where potential changes in current adoption schemes could be taken into account. In this section, quantitative benchmarks for SuDS implementation drivers and barriers are established along with guidelines which outline how they are evaluated. It is proposed that the following list of quantitative benchmarks listed in this section be used:

Proportion of Pollutants Removed

Improvement of water quality in waterbodies reported as polluted as a consequence of urban runoff (Section 2.1 and (SEPA, 2009)) can only be achieved by a reduction in the pollutants discharged to rivers and/or better management of urban surfaces. In addition, despite absence of clear relationship between the level of pollutants discharged and the level of biodiversity (Bishop et al., 2000a), better management of urban runoff has the potential to improve urban biodiversity and amenity.

The current approach to estimating the water quality benefits of SuDS schemes is based on the treatment volume approach. This approach undervalues the benefits that can be achieved by the use of SuDS not incorporating a permanent pool. This is despite performance of these SuDS on water quality improvements are widely acknowledged (Barrett et al., 1998; Legret et al., 1996; Scholz and Grabowlecki, 2007; Pratt, 1999; Collins et al., 2008; Legret et al., 1998; Illgen et al., 2007; Bean et al., 2007)). A move from the current water quality assessment is then desirable as a way to properly and accurately reflect SuDS water quality benefits, and hence their impact on the receiving water course, both in terms of quality and amenity/biodiversity.

In order to take into account not only the SuDS incorporating a permanent pool but the full range of SuDS techniques available, a move from the current water quality assessment is proposed in this project. The question of what could constitute a good water quality indicator is the subject of numerous investigations and is a source of debate (Wright Water Engineers and Geosyntec Consultants, 2010). This concern comes mainly from the stochastic aspect of the pollutants associated with raw runoff and the observed variability of SuDS techniques for the removal of SuDS pollutants as outlined in Section 2.2.3. However, despite this variability, long term observations lead to the development of modelling tools which should be seen within the uncertainties inherent to the modelling and the limited knowledge.

With regard to the current limited knowledge and current modelling packages available, it is proposed to use and estimate the proportion of pollutants removed as an indicator of the SuDS water quality benefits. This indicator allows the comparison of SuDS water quality performance of the different SuDS devices and a clear establishment of the discharged runoff pollutant concentration in the receiving environment. This approach is consistent with the results produced by most of the existing water quality packages (Section 2.5.2.1) and environmental standards implemented to reach good chemical and environmental status for receiving water bodies.

Regarding the drawbacks associated with using the proportion of pollutant removal as an indicator, the main concern is that the measure is highly dependent on influent water quality. Indeed, a system can be reported as achieving a good performance by treating highly polluted runoff while the same SuDS would achieve poorer performance if the runoff is only slightly polluted. The second criticism formulated concerns the wide range of definitions corresponding to the term "proportion of pollutants removed". Wright Water Engineers and Geosyntec Consultants (2010) summarised the different definitions commonly in use in the literature and underlined that "proportion of pollutants removed" could be estimated using either the inflow median concentration to outflow median concentration or the inflow median load to outflow median load. These calculations can be performed using mean of individual storm loads or on series of rainfall events. The different hypothesis employed for the determination of the "proportion of pollutants removed" leading to significantly different results (URS Greiner Woodward Clyde, 1999).

To address these issues, along with other reported research (Wong et al., 2006), the percentage of removal is defined by the percentage of load removal achieved between the water quality of the runoff before any treatment occurs and the water quality of the runoff of the effluent discharged in the watercourse for a determined series of rainfall events. The treatment efficiency should be seen in the context of the quality of the raw runoff and only water quality of the runoff discharged in the natural environment is comparable from a site to another and with potential water quality objectives for the receiving environment.

To determine the value of pollutant removal benchmark, MUSIC has been chosen as the main water quality package for this thesis. This choice was made at an early stage by reviewing the different water quality modelling tools (Section 2.5.2.1) and is based on MUSIC's potential to model a large variety of SuDS. The software provides an easy solution to model SuDS in series without using different models from different packages. The SuDS in the model have been pre-calibrated and allow the assessment of SUDS treatment train pollutant removal performances. Finally, despite the wide range of SuDS defined within the software, where a device is not available, it is possible to configure the model to represent its performance if field data is available.

Whole life cost

In order to estimate whole life costs, the investigations undertaken as part of the literature review have underlined two main techniques. The first is based on published costs for existing SuDS systems, while the second focuses on calculating theoretical costs based on up-to-date civil engineering prices (Langdon, 2009).

While the determination of the costs based on the published values for existing projects would constitute the more realistic option, the application of this methodology faces several key challenges. The first issue concerns the limited amount of data available in the public domain. What data is available relates primarily to common and widely used SuDS devices (Brown and Schueler, 1997), and there is only limited data regarding some other techniques (e.g. soakaways). The second issue concerns any site specific details: the economic studies of SuDS devices which have been published usually correlate the costs of construction and maintenance with the most dominant parameter driving the costs (i.e. the water volume). This approach is primarily due to the limited amount of data available and does not take into account site specific issues which can impact significantly on the overall cost of a project. Hence, although this is helpful in providing an insight into possible cost variability, the approach is limited.

Despite this observation, as part of this project, this approach has been used for the evaluation of costs and their variability as part of the Houston Industrial Estate case study where only a limited number of SuDS devices have been considered due to limitations on what could potentially be retrofitted to this area. However, this approach could not have been possibly applied for the Dalmarnock Road area where a wide range of SuDS devices have been investigated. Thus, the determination of the costs for SuDS types using the existing literature would prove to be difficult due to the sparse data currently available for some types of devices. As a result, the second technique, based on the bill of quantities, is used to estimate potential costs of construction and maintenance. This approach provides the opportunity to take site specific issues into account.

The length of time over which SuDS maintenance needs to be estimated is also subject to discussion as different durations varying from 20 to 60 years have been used by different authors to evaluate SuDS whole life cost (Wong et al., 2003). There are no established rules regarding the length of time over which whole life costs need to be estimated. For the reported research, duration of 50 years was selected based on research reported by UKWIR (2005). It has been thought that the choice of 50 years duration would provide a realistic estimate of a SuDS lifetime and allow competing solutions to be compared. Although the net present value of maintenance costs beyond that time horizon are negligible, it is important to note that a smaller duration may have had a significant impact on the results.

Attenuation volume

In response to both flooding issues at downstream location and channel modification hydrology (Section 2.1.2), SuDS are often a solution to attenuate runoff for different return periods based on guidance (Scottish executive, 2001; Scottish Executive, 2004). The ability of SuDS to mitigate the adverse hydraulic effects linked to the development of impermeable surfaces has been considered by estimating the attenuated volume.

Depending on the site, the development of large impermeable surfaces impacts on hydrological conditions by reducing the potential volume infiltrated and reducing the time of concentration. The potential consequences are an increase of the downstream flood risks, a reduction of the groundwater recharge and a modification of the channel hydrology (Section 2.1.2). The consequences have a different impact depending on the site location and the catchment conditions. For example, a reduction of the infiltrated runoff may be considered critical in an area with a hydrological stress but will be considered differently where the risk of water shortage is reduced. The impacts of the consequences being very different from a site to another, the measures to put in place may vary and are taken in accordance with the potential impacts by the environmental regulator and the local authorities (Thevenot, 2008).

The cases studies presented in this research, the Dalmarnock Road area and the Houston Industrial area, are situated in the south of Scotland. Preliminary discussions with the stakeholders and investigations related to the two case studies have shown they were unlikely to suffer from potable water stress, the water being provided by numerous reservoirs with sufficient capacity. Consequently, the recharge of the ground water is unlikely to be a priority objective when implementing SuDS devices. Moreover, as the soil is likely to be polluted, the opportunity for runoff to be infiltrated is limited. The opportunity presented by SuDS to recharge groundwater have hence been put aside at an early stage in the holistic assessment as this was not considered as a valuable asset for the case studies considered. However, it is recognised that SuDS can contribute greatly to groundwater recharge and this may be a valuable asset in countries suffering from potable water stress (e.g. Australia).

However, runoff discharges are likely to have an impact on downstream flooding. This is especially true for the Dalmarnock Road area where the development lies upstream of important developments. Discussion with Glasgow City Council representatives have underlined the conflicting issue between the willingness to attenuate the flow in regards to downstream developments and the additional land necessary to attenuate high return period design storms. For this area, three attenuation scenarios have been retained and are investigated:

- no attenuation;
- limited attenuation (30 years return period); and,
- robust attenuation (100 years).

The situation is different regarding the Houston Industrial Estate where an investigation undertaken by SEPA (SEPA, 2012) concluded that no developments were currently at risk of flooding downstream of the area due to be redeveloped. Consequently, only the no attenuation and limited attenuation scenarios are investigated.

The different attenuation scenarios for the cases studies are modelled with Infoworks CS. The modelling of SuDS hydrologic components was modelled based on available performance characteristics reported in literature and the design likely to be adopted.

Land take

In the context of the different techniques available to implement SuDSsolutions, the implementation of some SuDS can neutralise valuable developable areas. This is particularly true for regional controls such as ponds and wetlands estimated to take up to 10% of the development space (CIRIA, 2007). This loss of space is seen negatively by developers and planners, especially in high density developments and can prevent an efficient return on investment to be made. While the development of source and site controls are also seen negatively, the benefits achieved in terms of attenuation and water quality can be used to reduce the land allocated to regional controls.

In this context, the land taken by the different SuDS controls and intrinsically how they can prevent or allow further development to take place is a key indicator. The land occupied by SUDS devices is taken into account in the holistic assessment of the treatment train and a particular attention is paid on evaluating by how much regional controls can be reduced if upstream techniques are used to reduce pollutant load and attenuate the flow.

The main criticism that can be formulated on using land take as a benchmark is that SuDS cannot be considered equally depending on the area considered, the type of development (Valuation Office Agency, 2010a; Valuation Office Agency, 2010b) and the location of the SuDS devices within the development.

To face this criticism, it has been considered in first instance that the land take of source controls, relatively small and on private land (e.g. soakaways, water butts) are not considered in the evaluation of the land take. The basis for this is that they are not considered as reducing the space available for development. The remaining SuDS devices contributing to the treatment train have been summed to provide an estimate of the SuDS treatment train land take to compare with the use of SuDS end-of-pipe controls.

Willingness to pay for amenity and biodiversity assets:
Biodiversity and the underlying amenity provided by SuDS to local residents has been felt as a key asset for the establishment of treatment trains. Indeed, research presented has shown the importance of amenity and biodiversity to residents living in close proximity to SuDS regional controls (Apostolaki et al., 2006). Early research has shown that this interest could potentially be valued by either increasing the potential attractiveness of the area or increasing the sale value (USEPA, 1995). In the context of the treatment trains, the benefits achieved in terms of water quality by upstream SuDS controls can help in increasing the amenity and biodiversity potential achieved by regional controls. These benefits can potentially be evaluated by developers and planners by increasing sales value and/or the saleability of their product.

In order to understand the potential impact of upstream regional controls and how they are linked to amenity and biodiversity potential of SuDS regional controls, targeted interviews with residents living in close proximity to regional controls has been undertaken. The targeted interview aimed at determining the impact of using SuDS source and site control, and intrinsically on water quality, wildlife and amenity potential generated by regional controls. The key benchmark used to establish correlation with wildlife and amenity potential is the willingness to pay. The drawbacks, the methodology and the results obtained from the resident's interviews are presented in the Chapter 4.

3.3.3 ANALYSIS OF THE RESULTS (PHASE 3)

The methodology developed allows a comparison between the different SuDS scenarios for a development to be made. This assessment is reached based on key benchmarks determined based on stakeholders interviews and reflect drivers for and barriers to the implementation of SUDS in the context of current legislation and guidance.

The comparison which is made for the different scenarios allows the establishment of the following:

- A comparison of the benefits achieved by the different treatment solution with regard to the potential benefits achieved by an end-of-pipe system, and;
- A comparison of the drawbacks achieved by the different treatment train solutions with regard to the potential drawbacks achieved by a end-of-pipe system.

These comparisons aid in the determination of whether the benefits associated with the development of a full treatment train are sufficient to offset the perceived drawbacks. These considerations allow the evaluation of whether changes suggested as the hypothesis for this research (Section 1.2) are sufficient or if a more constraining framework is needed to encourage SuDS treatment train uptake.

3.4 CONCLUSION

This section has identified the current drivers for and barriers to SuDS implementation. This identification, based on interviews and literature reviewed regarding SuDS implementation in Scotland and elsewhere, has permitted the creation of a set of quantitative benchmarks which are meaningful to stakeholders. These quantiative indicators can be estimated at the design stage based on recent guidance for Scotland and using modelling tools. The proposed methodology presents a shift from the traditional evaluation of SuDS systems for several reasons:

- The evaluation of water quality performance is not done on the notion of captured volume as presented in Section 2.3.3, but on the treatment efficiency of the device. While this approach prevents comparisons between sites, it allows all of the SuDS techniques to be taken into account when estimating water quality performance of the treatment train.
- The establishment of quantiative indicators allow straightforward comparisons of SuDS drivers for and barriers to the implementation of SuDS devices. These quantiative indicators allow the formulation of relationships between barriers and drivers.
- The presentation of several treatment trains, including varying techniques and a varying number of SuDS in series, allow the comparison of the benefits and drawbacks of using several SuDS in series. The results establish for a specific pollutant removal and specific return period attenuation, the relationship between land take and costs for different treatment trains. These relationships

between land-take and costs can be used by stakeholders as a basis for discussion to identify the most suitable solution.

Application of this approach to key case studies representative of common SuDS implementation situations test the research hypothesis and establish a framework for the development of SuDS treatment trains.

Chapter 4 - Valuing Amenity - Public perceptions of SuDS ponds in Scotland

4.1 Introduction

SuDS techniques include a wide range of different tools (CIRIA, 2007) that should be used in a series to treat and attenuate runoff to the required standard (SEPA, 2006). Amongst the SuDS techniques available, ponds and wetlands, which include a permanent pool of water and vegetation, are regarded as having a high potential to be a source of biodiversity and amenity in urban development and help to improve health and well-being in cities (Pretty et al., 2007; Song et al., 2007; Velarde et al., 2007). The interests of stakeholders, including the environmental regulator and sewerage undertaker, to include SuDS in new developments are generally known (Wild et al., 2002) but the view of residents living in close proximity to SuDS is still not fully understood. This is key as positive public perception will ensure ponds and wetlands satisfy not only water quality and water quantity objectives but bring amenity in developments according to the SuDS triangle (Bastien et al., 2010a).

4.2 SuDS public perception and contingent valuation

The public perception of SuDS structures has been investigated by other researchers: Yuen et al. (2005) demonstrated that green roofs have a positive impact on residents in high density areas. Similarly, the perception of rainwater harvesting by local residents was investigated by Ward et al. (2009) who demonstrated that residents were keen on reusing the water from their own roof but reluctant to recycle runoff from other sources. Whether it concerns aesthetics improvements, access and community benefits or potential for public education and awareness (CIRIA, 2007; Ellis et al., 2004), the term amenity has often been used to characterise the potential benefits the residents could find in a project. With respect to retention ponds specifically, Apostolaki et al. (2006) summarised the results of door to door public perception questionnaires conducted at UK sites between 2000 and 2002 amongst residents adjacent to 10 ponds situated in Scotland, England and Wales. The survey was in the form of an open ended questionnaire and aimed at assessing public perception of SuDS ponds, including potential benefits and disadvantages. Overall, the survey demonstrated that there was significant interest in ponds and residents felt that the presence of a well established pond could increase property value by up to 10%. Within the context of current surface water management, where costs have been identified as one possible barrier for SuDS implementation (McKissock et al., 2003; Todorovic et al., 2008a), it may be argued that charging residents a factoring fee, based on the additional value that pond amenity provide, could help to offset water management costs. Within this context, the work conducted in 2004 and presented by Apostolaki et al. (2006) has highlighted that an opportunity exists to offset SuDS costs with the benefits they provide to homeowners and residents.

Evaluating environmental goods in terms of monetary value has always been seen as a difficult task (Ebert, 2008). However, two main techniques have emerged which allow their assessment: the hedonic valuation and the contingent valuation methods. Hedonic pricing relates to the observation of house price variations due to different factors. This approach has been used to investigate the economic value of urban green space in numerous surveys undertaken in high density environments (Kestens et al., 2004; Kong et al., 2007; Luttik, 2000) and has generally demonstrated the positive impact of green spaces on property value. Furthermore, the use of the method to value a detention basin associated with multipurpose green space found that the device had a positive impact on property values, while a detention basin without any green features was shown to have no discernable impact (Lee and Li, 2009). Despite these results, the hedonic valuation of environmental benefits is not an easy exercise as it requires significant data on property values and the choice of variables selected by authors can appear quite subjective. In contrast, the contingent valuation approach consists of asking, through a structured interview, the price the respondent would be willing to pay for market or environmental goods. Compared to hedonic pricing, the contingent valuation method requires less data on the surroundings, but relies heavily on the respondents' willingness to participate. Despite this, it has been applied successfully to determine the value associated with environmental benefits (Arrow et al., 1993).

In summary, the work presented here aims to augment and update knowledge in this area of research by providing:

- an understanding of the benefits ponds provide and an estimate of their perceived value to residents and homeowners; and,
- a comparison with the work previously undertaken, in particular, to understand how public perception has changed in the 7 years since the last detailed study was undertaken in the UK.

4.3 METHODOLOGY

An understanding of the benefits SuDS ponds provide and an estimate of their perceived value to residents and homeowners was determined through the use of a structured questionnaire. The questionnaire objectives were:

- to identify how the presence of the pond influences people to move to an area.
- to understand public awareness of the pond and its SuDS function.
- to identify resident perception of the pond, including perceived advantages, wildlife and disadvantages; and,
- to determine, through contingent valuation, the potential monetary value associated with the pond.

It should be noted that the term “wildlife” is used here as residents could not reasonably be expected to provide a response which can be objectively used to quantify “biodiversity”.

Once the questionnaire was constructed, a pilot survey was conducted using face-to-face interviews in May 2009 to identify and refine any unclear parts. The pilot questionnaire was trialled at two pond locations with four interviews being conducted at each to ensure that the questions were understandable and that participants had sufficient information to answer questions. The refined questionnaire available in appendix 1 comprised four parts (McLoughlin, 2009):

- An introduction presenting SuDS.
- Specific questions targeting pond perception from residents point of view.
- A financial part to establish the willingness to pay for any benefits associated with the pond.
- Demographic questions and opportunity to participate in a prize draw.

The questionnaire deployed had evolved significantly from the questionnaire used by Apostolaki (2005) by providing questions on perceived wildlife, pond maintenance and perception of pollution. While Apostolaki’s questionnaire included a question on the potential increase in property value, the presented questionnaire attempted to be more specific by requiring the residents to specify how much they would be willing to pay for the benefits presented by the ponds. This approach was clearly aimed at understening how residents could contribute to ponds’ construction costs and maintenance while understanding how these were impacted by pond perception.

The questionnaire was distributed among residents living near well established ponds located in and around Edinburgh (Figure 4-1). Although none of the ponds were part of a formal treatment train, their settings are quite different as reported in Table 4-1 and Table 4-2 where the key features of the ponds are presented.

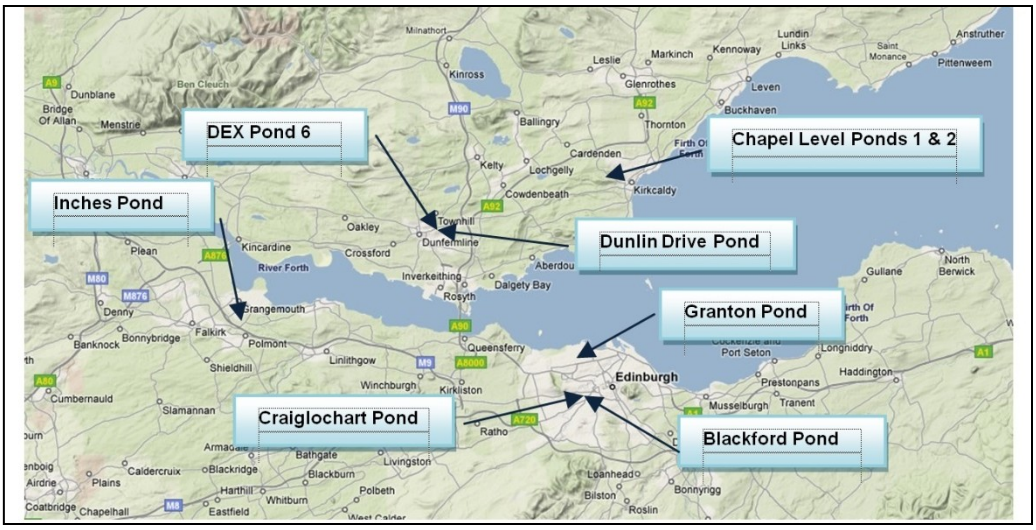


Figure 4-1: Location of the eight ponds targeted in the survey

Location	Inches Pond, Larbert	Chapel Level Pond 1, Kirkcaldy	Chapel Level Pond 2, Kirkcaldy	DEX Pond 6, Dunfermiline
Draining area	Residential roofs and roads	Residential roofs and roads	Residential roofs and roads	Residential roofs and roads
SuDS Type	Detention Pond	Detention Pond	Detention Pond	3 Linked Detention Ponds
Approximate pond size (Ha)	~ 0.05	~ 0.5	~ 0.5	~ 0.5
Functions	Attenuation and Treatment	Attenuation and Treatment	Attenuation and Treatment	Attenuation and Treatment
Construction period (circa)	2000	2005	2005	2005
Ownership and maintenance responsibilities	Scottish Water	Scottish Water	Scottish Water	Scottish Water
Access to the water body	Very limited with fencing and reed beds	Double fencing, bushes and reeds.	Double fencing, bushes and reeds.	Very limited with fencing and reed beds
Additional amenity features	Path along the pond	None	None	Path around the pond

Table 4-1: Pond details (1)

Location	Dunlin Drive Pond, Dunfermline	Granton Pond, Edinburgh	Craiglochart Pond, Edinburgh	Blackford Pond
Draining area	Several hundred houses and access roads	Commercial development	1 Large building and access roads	Roads Only
SuDS Type	Detention Pond	Detention Pond and Wetland	Pond	Pond and Wetland
Approximate pond size (Ha)	~ 0.5	~ 0.5	~ 1	~ 0.8
Functions	Attenuation and Treatment	Recreational, Attenuation and Treatment	Recreational	Recreational and Ecological
Construction period (circa)	2005	2008	1878	1848
Ownership and maintenance responsibilities	Scottish Water	Private	Edinburgh Council	Edinburgh Council
Access to the water body	Limited with fencing	Limited with low height vegetation	No restrictions	No restrictions
Additional amenity features	None	Pond integrated to a parc. Path along the pond with a bridge across the water	Pond integrated in the border of a forest. Include a path along the pond	Pond integrated in the border of a forest. Include a path along the pond

Table 4-2: Pond details (2)

Figure 4-2: Blackford pond

Figure 4-3: Chapel Level 2 pond

Figure 4-4: Dex pond 6, Dunfermline

Figure 4-5: Chapel Level 1 pond

Figure 4-6: Granton pond, Edinburgh

Figure 4-7: Dunline drive pond

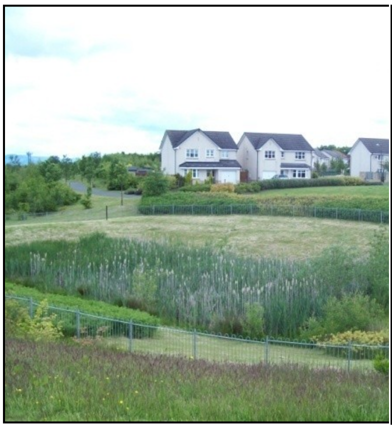


Figure 4-8: Inches pond, Larbet

Figure 4-9: Craiglochart pond, Edinburgh

4.4 RESULTS AND DISCUSSION

4.4.1 RESPONDENTS DEMOGRAPHIC AND LOCATION

To be eligible to receive the questionnaire residents had to live within 5 minutes walk (400m) of one of the selected ponds. This was to ensure residents had ready access to the pond and that most of them would be aware of its existence. A total of 400 questionnaires were distributed to households in proximity of the 8 selected ponds. Of the 400 issued, 108 questionnaires were returned although some were not fully completed. 107 questionnaires were deemed to contain exploitable answers and equates to an overall response rate (RR1) of 27% according to the AAPOR definition (The American Association for Public Opinion Research, 2009). Whilst the response rate may appear modest, these figures are in the range of what could have been reasonably expected in comparisons with previous surveys (Apostolaki et al., 2006). The response rate and sample size mean that the margin of error is ±7.2% at the 95% confidence level. Respondent's details may be found in Table 4-3. In contrast to earlier studies, 94% of the respondents stated that the pond was in place when they moved to the area.

Age (%)		Location (%)		Situation (%)	
<18	1	Blackford Pond	18	Tenant	8
18-24	0	Chapel Level Pond 1	10	Owner	92
25-34	8	Chapel Level Pond 2	13		
35-44	32	Craiglochart Pond	19		
45-54	32	DEX Pond 6	10		
55-59	7	Dunline Drive Pond	9		
60-65	5	Granton Pond	5		
>65	12	Inches Pond	16		
N/A	2				

Table 4-3: Demographic and location characteristics of the survey respondents (%) (n=107)

To understand the social background of the responders, the Scottish Index of Multiple Deprivation (SIMD) (Scottish Executive, 2009) was used. This uses 31 indicators such as income, employment and housing to classify over 6500 areas in Scotland as a function of their level of "deprivation". Apart from the Granton area, the SIMD database reports that the areas considered cannot be defined as "deprived" – all are in the top 40%. Although the Granton pond is located in an area reported as being more deprived, it is newly established in a recently developed area and is likely to become a sought after area in the next few years. Overall, the areas surveyed are likely to be populated by people from higher socio-economic groups. Indeed, the majority of the respondents were home owners aged between 35 and 45 years (64.6%).

4.4.2 THE ACCOMMODATION IN CONTEXT

When asked if the presence of the pond affected their decision to move into an area, only 32% of the respondents said that it had a positive influence, whereas 66% claimed it did not make any difference and only 2% reported that it had a negative impact. These results must be treated carefully, as there was significant variation between sites. Indeed, for the same question, 63% of the residents adjacent to the Craiglockart pond report that it had a positive influence, whereas for Inches pond 100% of respondents say it made no difference. When asked to specify the factors influencing their decision to move to an area, the accommodation itself came first with 72% of the respondents answering it is the most important, with location and surroundings achieving only 38% and 28% respectively. When specifying important surrounding factors, respondents clearly indicated that a safe environment was the primary focus (Figure 4-10). Secondary factors included access to facilities, visual aspect and importance of green space. When asked to detail how they considered the safety of a natural pond compared to other urban infrastructure, roads and rivers were both considered as being more dangerous (Figure 4-11). This is an important point as the potential health and safety risks posed by SuDS ponds, despite the inclusion of low slopes, barriers and planting, must be placed within the context of that presented by other elements of urban infrastructure. This point has also been noted for other risks posed by urban drainage infrastructure (Arthur et al., 2009).

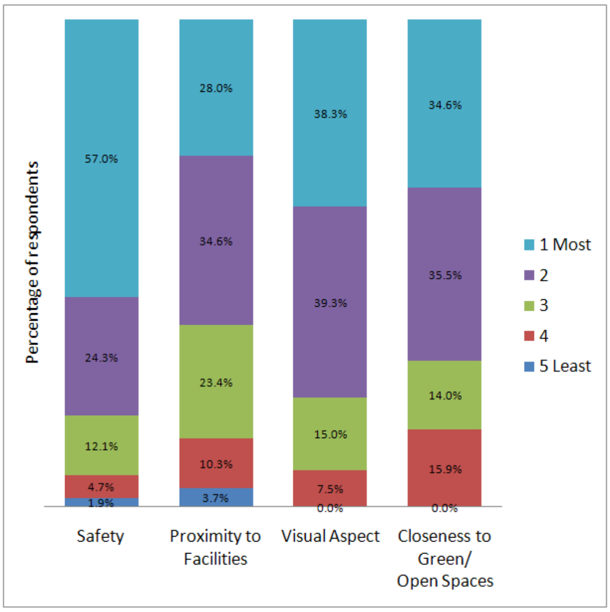


Figure 4-10: Important neighbourhood factor

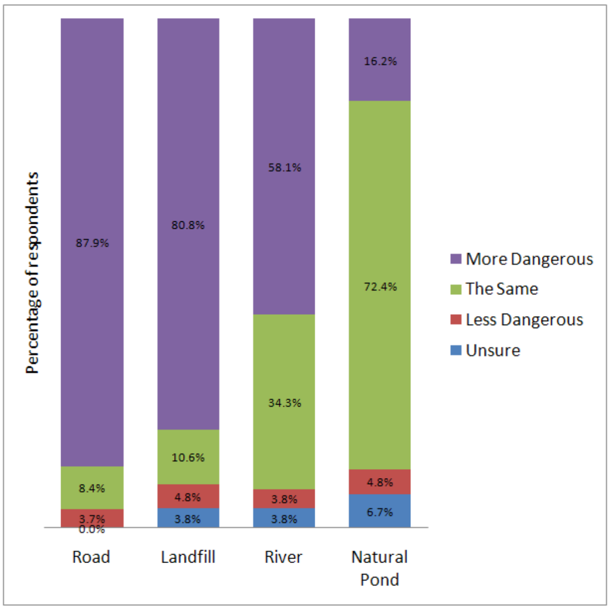


Figure 4-11: Safety perception

4.4.3 Pond perception

The second part of the questionnaire was concerned with identifying how the public perceived the pond - either in a positive or negative way.

Advantages. Regarding the benefits provided by the pond, the perception of wildlife, in the form of a number of wild species identified by the residents, achieved top ranking, with 76.5% of the respondents identifying it as the most important benefit (Figure 4-12). Any additional value provided to their home by the pond was not considered by the respondents as this achieved the lowest ranking. These results are largely site specific as Blackford and Granton ponds achieve a high ranking regarding wildlife with 84% and 100% of the respective respondents mentioning it is the most important function (Figure 4-13). The majority of the respondents (74%) claimed they were aware that the pond is able to perform as a SuDS (i.e. treating pollution and attenuating the flow) and 69% of the respondents identified that drainage was one of the most important benefits (Figure 4-12). This high level of awareness was may have been influenced by 1) by the introduction to the questionnaire pinpointing the role of SuDS ponds to justify the survey and, 2) by previous surveys on SuDS ponds (e.g. Apostolaki, 2005).

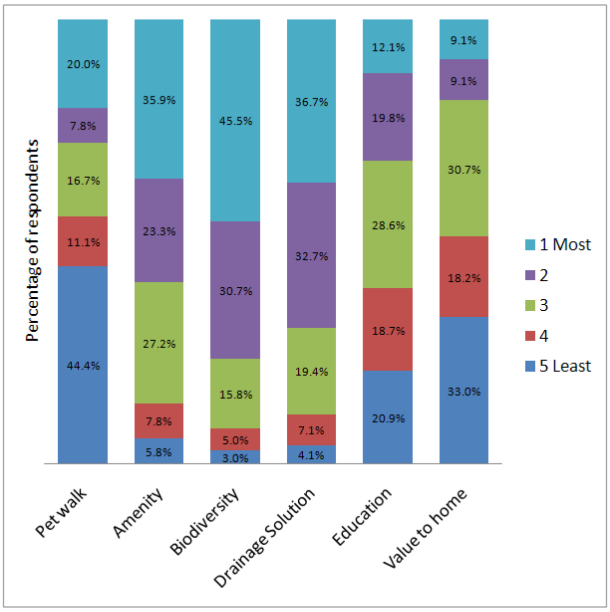


Figure 4-12: Most important benefits of living close to a pond

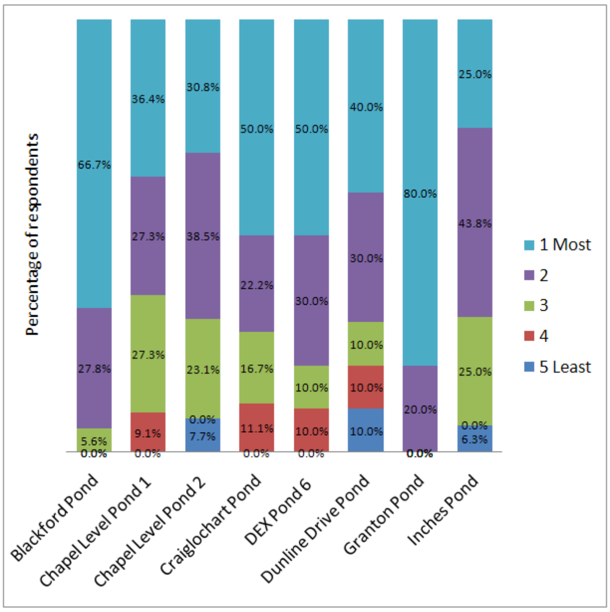


Figure 4-13: Perception of SuDS as a primary wildlife enhancing measure

Disadvantages. As demonstrated previously, safety is one of the top concerns when selecting a home. When asked to specify the disadvantages of living in close proximity to a pond, safety is seen as the most significant disadvantage, with 32% of the respondents stating this (Figure 4-14). Although the ponds were well established, this result contrasts with previous work where safety concerns were mostly attributed to newly established ponds (Apostolaki et al., 2006), and well established ponds were considered rather more positively by residents. The second most common concern was rodents (21%). However, it is likely this response represents a fear rather than a real observation, as neither mammals nor reptiles were commonly spotted at any pond location.

Once more, it should be noted that the results presented here are means and that there was significant variations between sites. This point is illustrated in Figure 4-15, where it can be seen that, for the Dunline pond, respondents identified safety as one of the most important concerns. Conversely, safety at the Craiglockart pond achieves a comparatively low score. A further point of note is that the highest safety concerns (above 60%) were associated with ponds designed to Scottish Water standards. In contrast, ponds designed to different standards (privately or council owned) and hence not necessarily providing obvious safety measures are not perceived as particularly dangerous (scores below 50%). This demonstrates that specific safety measures taken by Scottish Water (including barriers, low gradient slope and reed bed protection) may have failed to reduce the hazard level perceived by residents.

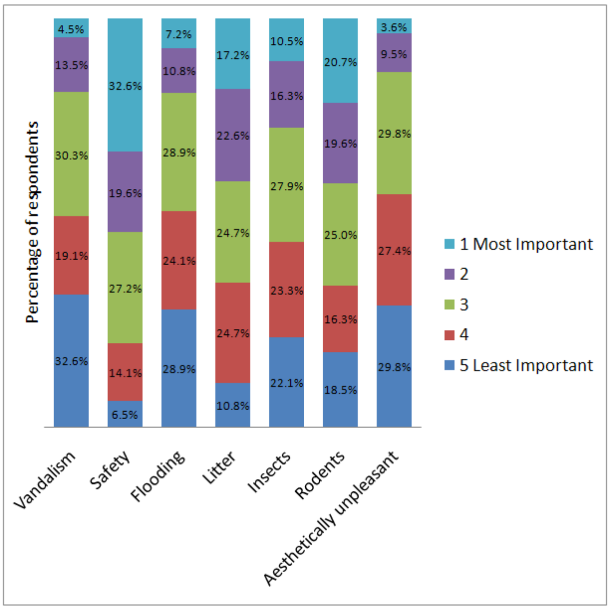


Figure 4-14: Perceived disadvantages of living in close proximity to a pond

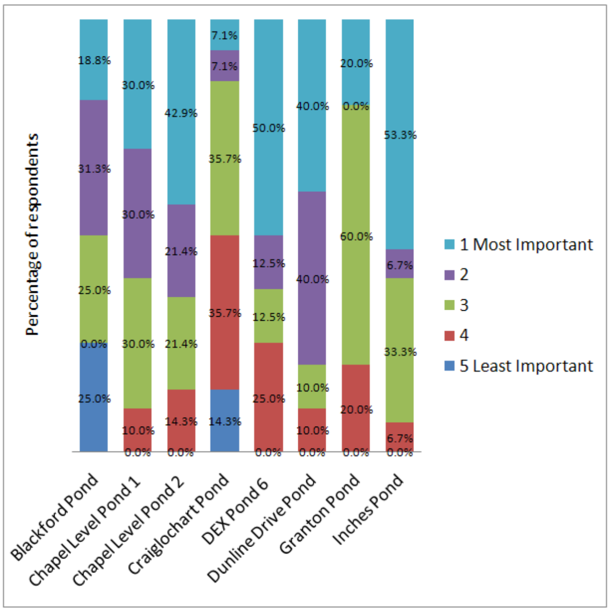


Figure 4-15: Safety perception at different pond sites

The second most significant concern was pollution. However, this was most heavily linked to the aesthetics of the pond - the most common form being litter (Figure 4-16). Once more, the results varied from one pond to another with Granton, Craiglockart and Blackford locations achieving the top three cumulative scores (Figure 4-17). These scores are highly related to the maintenance perception: when asked whether they thought the ponds were appropriately maintained or not, locations achieving the lowest scores were also Granton, Blackford and Craiglockart with respective scores of 75%, 57% and 47%. A chi-square test with a 5% level of significance reveals that there is a strong correlation between perception of the ponds' need for maintenance and the amount of litter respondents have been able to spot in the pond: the presence of litter clearly affects the perception residents have of their pond and how it is maintained.

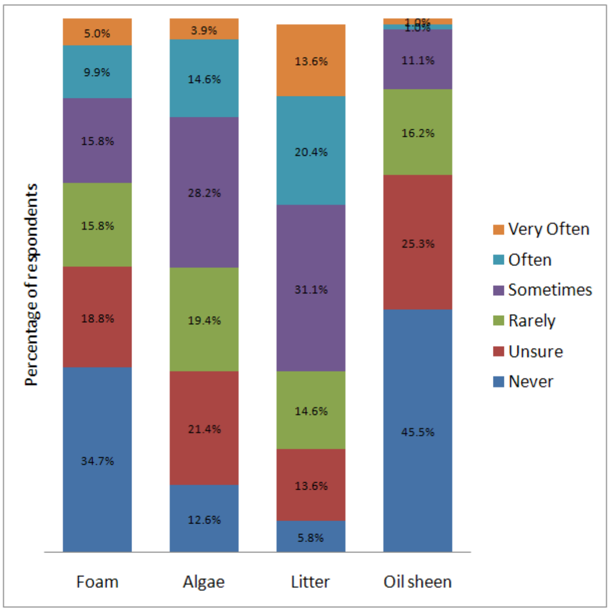


Figure 4-16: Observed pollution in close proximity to ponds

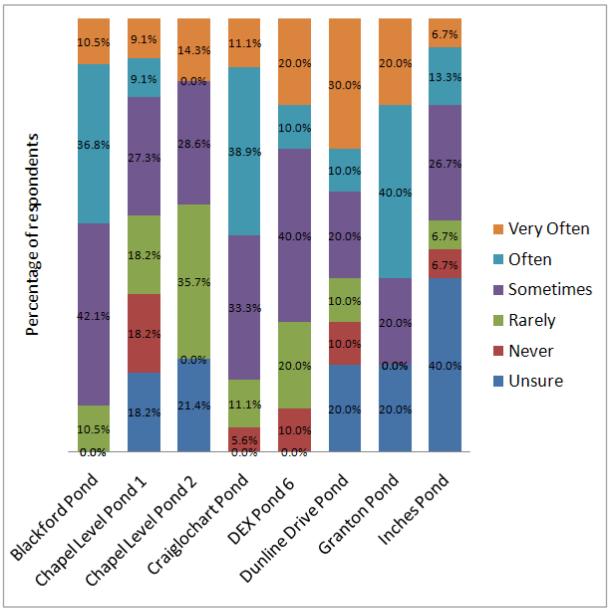


Figure 4-17: Litter spotted in close proximity to ponds by location

Wildlife. Regarding wildlife spotted by residents, respondents identified birds (small and large) as the most commonly spotted animals whereas insects, amphibians and mammals occupy the next places. Reptiles, uncommon in Scotland, were seldom spotted by the residents. The observation of wildlife is largely influenced by the location of the pond and its surroundings. Figure 4-19 shows that Craiglockart and Blackford ponds were perceived as having the highest wildlife presence, with both locations having over 70% of birds spotted by residents.

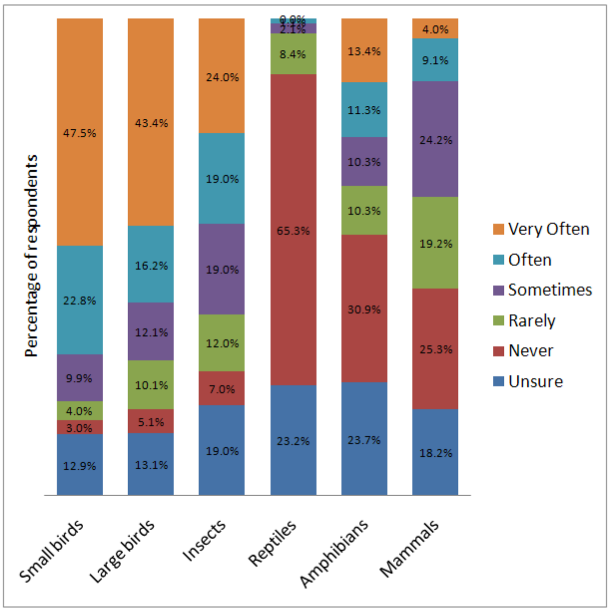


Figure 4-18: Types of wildlife spotted.

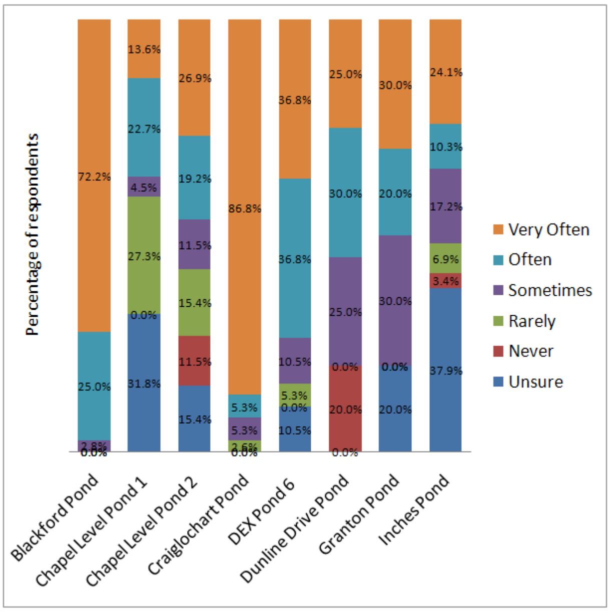


Figure 4-19: Large and small birds observation at each pond

4.4.4 COMPARISON WITH PREVIOUS WORK

Although the presented research was undertaken using a wider range of sites and had a higher number of responses than that used in other projects, it is possible to make comparisons:

- Apostolaki et al (2006) reported low levels awareness of SuDS systems and their functions, with only 6% of respondents having knowledge of how they are expected to perform. In contrast, the reported research found that 26% and 42% of the respondents claimed they were aware or vaguely aware respectively of the pond's function. This finding may reflect increased awareness of environmental issues.

- Some advantages are preponderant on others. For example, the presence of wildlife (largely small and large bird species) is perceived as being a key benefit, followed by drainage performance and amenity. Education, pet walking area and increased property values were perceived as secondary advantages. These results are similar to those obtained by Apostolaki et al (2006), the only substantive difference being increased awareness and appreciation of the drainage function. Again this may highlight an increased awareness of sustainable development and urban flood risk management.
- There is no substantive change in health and safety perception despite recent efforts to improve safety (CIRIA, 2007; Scottish-Water, 2007). Residents continue to perceive ponds as a potential hazard. However, this should be placed within the context of the perceived risks associated with other elements of the urban fabric. For example, in 2005, 8.7% (38) of all UK accidental drowning happened in urban areas. Of these, 6 were in ponds and 25 were in baths. In the same year, there were 1099 deaths and 164,298 injuries on urban roads (ROSPA, 2005).
- Litter spotted around ponds remains an issue for residents. This observation places extra emphasis on the need for frequent maintenance to improve the amenity provided by the pond.

4.4.5 FINANCIAL

The monetary value associated with the presence of the pond was assessed using the contingent valuation (CV) methodology based on a recognised methodology (Arrow et al., 1993). In the final part of the questionnaire, respondents were asked if they thought the potential benefits of living in close proximity to the pond could offset the perceived disadvantages. A total of 60% of the respondents answered yes, 26% were unsure and only 14 % answered no. A chi-square test with a 5% level of significance was used to conform the statistical significance of any correlations between this question and the previous questions answered by the respondents. A statistically significant link was found for the following:

- Respondents who have direct visual access to the pond from their lodgings felt that the pond had a positive impact that could offset the potential disadvantages.

- Similarly, there was a significant link between those who valued the wildlife provided by the pond and those who felt that benefits could outweigh disadvantages.
- Conversely, those who felt litter was a problem also felt that benefits could outweigh disadvantages.

Those residents who viewed the pond positively were asked to give an estimate of the monetary value they would be willing to pay monthly to find similar advantages to those offered by the pond in another location. Thus, this question was asking them to associate the perceived benefits associated with the pond with a monetary value. Although a good cooperation rate of 82% for this sensitive question was achieved, the most common answer was £0.00 with 50%. The absence of answer (18%) was interpreted as a refusal to pay and was encoded as £0.00.

The average willingness to pay (Table 4-4) for the different ponds varies from site-to-site. Privately or council maintained ponds (Blackford, Craiglockart and Granton) are clearly in the top of the ranking whereas ponds designed and maintained to Scottish Water standards achieve a lower willingness to pay value. With a weighted average willingness to pay of £18.71, privately or council maintained ponds clearly outrank those designed to Scottish Water standards (£5.62). This result indicates that the perception of ponds designed to the Scottish Water standard is below the perception of other privately or council maintained ponds. Consequently, despite recent guidelines design of Scottish-Water ponds vesting criteria.

Pond location (sample size)	Average willingness to pay (£/month)
Pond 6 Dex (11)	3.20
Chapel level 2 (15)	3.60
Inches (17)	5.00
Dunline (10)	8.00
Chapel level 1 (11)	9.60
Blackford (19)	15.70
Craiglockart (20)	20.00
Granton (5)	25.00
Weighted average (108)	10.95

Table 4-4: Contingent valuation for the different sites

For all the locations combined, an average £10.95 per month per dwelling for the residents living in close proximity to ponds has been established. Based on the costing methodology recommended by HM Treasury (2003), the net present value of the average willingness to pay over 50 years is calculated by adjusting future willingness to pay with a discount rate of 3.5% up to 30 years, followed by 3% for the remaining years. The equivalent amount of money corresponds to £3324 per dwelling over a 50 years period and it is thought that residents contribution could help in offsetting construction and maintenance costs of ponds although the way money could be collected is not discussed here.

To offset the cost of building and maintain a pond to the amenity provided to those living in close proximity, it is important to consider minimum development densities. As a case in point, assuming a high maintenance level and using published data (Bastien et al., 2010b) to determine construction and maintenance costs, the net present value of a 2400m^3 pond capable of draining a 20 hectare residential area has been estimated to be around £227k. Assuming that 7 ha of development would have access to the pond in similar conditions to that presented in the survey, a density greater than 10 dwellings per hectare is sufficient to offset the costs of construction and maintenance of the pond over a 50 years period.

4.5 CONCLUSIONS

While not directly influencing the choice to move into an area, even for well designed systems, ponds offer advantages that residents have been able to clearly identify. In summary, based on the research presented in this paper it is possible to draw the following conclusions:

- Residents have identified wildlife as the most important benefit, and this impact on their potential willingness to pay. This finding underlines the need to use treatment trains before runoff is discharged to a pond to manage runoff quantity and quality efficiently, and thus maximise wildlife and amenity potential (Helfield and Diamond, 1997).
- Confirming the findings of previous studies, health and safety risks were identified as the main concerns of residents. However, these should be seen as site specific and low relative to other urban risks. Despite the relatively low number accidents reported due to drowning in waterbodies relative to other urban hazards, recent guidelines which aim to reduce any threat ponds pose appear to have had a limited impact on the perception of residents. Raising

awareness and informing residents on the nature of the risks posed may be the key to gaining greater acceptability of SuDS ponds.

- Pond functions are generally well understood and the presence of litter, even if it is felt as a disadvantage, is not an obstacle to residents and does not affect their willingness to pay.
- The average potential benefits generated by the amenity provided the pond could serve to offset construction costs and maintenance of the pond. Application to a case study has shown that even a very low urban density development would achieve sufficient potential monetary benefits to offset the cost and maintenance of the pond over a 50 year period.

4.6 IMPORTANT REMARKS AND IMPACT OF THE RESEARCH ON CURRENT WORK

The current investigations undertaken to understand the perception of public SUDS should be placed in the context of the current research undertaken to understand how the treatment train implementation could be facilitated.

Confirming the findings of previous studies, health and safety risks were identified as the main concern for residents. However, health and safety perception should be seen as very site specific and low relative to other urban risks. Thus, although health and safety has been reported as one of the main issues during the interviews with the different stakeholders and reported in Section 3.1 as well as confirmed by residents' interviews, this issue can easily be managed through the improvement of pond design associated with a better education on ponds benefits. The ponds designed following CIRIA's (2007) recommendations, instead of those from Scottish Water, have proven to benefit from less health and safety concerns. Thus changes in the recommendations for the design of ponds due to be adopted by Scottish Water is key to a better public perception and a reduction of the health and safety issues perception. According to this remark, no further consideration has been given to health and safety issues in the next chapters.

Despite the presence of litter spotted in close proximity to ponds, there were no collations with the willingness to pay at the different sites. However, litter has been reported as a significant issue for residents (slightly less significant than health and safety issues). This underlines the need to have well maintained schemes which optimise benefits to the public / residents. As consequence, it is assumed that systems will be maintained to a high standard, including a frequent litter removal. Accordingly, the determination of the costs using the bill of quantities methodology described in Section 2.5.3, when applied, will assume high maintenance standards (and costs) apply.

Residents identified wildlife as the most important benefit of living in close proximity to a pond. Within this context, wildlife has been used as a term to characterise fauna and flora elements non experts have been able to spot in close proximity to water bodies. This term has been used voluntary and real measure "biodiversity" requires more detailed understanding and surveys. Notwithstanding, previous research has shown how the degradation of the water quality has impacted on biodiversity and hence wildlife (Adamek et al., 2001). Consequently and although none of the ponds investigated was using a treatment train, the protection of the water quality in regional control using source and site controls is recommended as part of the treatment train philosophy to protect biodiversity in regional controls (Helfield, 1997). Thus, despite the problems associated with establishing a clear link between water quality and wildlife, the two are qualitatively correlated. Considering this, the water quality benchmark, estimated using the site specific percentage of removal as specified in Section3.3.2, also encompass a qualitative estimate of the biodiversity and wildlife benefits achievable at the regional control.

The willingness to pay for the potential amenity provided by the pond has shown to be highly variable depending on pond schemes. Although some very low values are achieved for poorly designed ponds, the average willingness to pay correlated to relatively low urban density, is sufficient to offset potential costs of construction and high standards maintenance of a site specific pond. Although this result should be seen within the variability associated with the costs of construction and maintenance of ponds and within the context of land values, this result clearly demonstrates that the benefits obtained from well designed and maintained ponds can be used as a funding mechanisms for the construction of ponds. This point is discussed further in Chapter 6 when detailing possible improvements to facilitate treatment train implementation.

Although the willingness to pay for amenity and biodiversity can in some cases be significant and help overcome construction costs and maintenance for ponds, it will not be considered further in this thesis two several reasons:

1- The willingness to pay has been shown to be highly variable depending on pond characteristics. The wide range of responses render it difficult to assess the potential return on investment that could potentially be made at the design stage.
2- At the time of investigation, there are no legal schemes for maintaining SuDS schemes based on funding provided by local residents.

Chapter 5 - FEASIBILITY STUDIES: DALMARNOCK ROAD AREA AND HOUSTON INDUSTRIAL AREA

The methodology outlined in Chapter 3 is applied to three cases studies with distinct sites, land uses and catchment characteristics. The Dalmarnock Road Area, a residential area due to be redeveloped, is taken as a basis to investigate the implementation of treatment trains on a brownfield area, the realistic case, and on a greenfield area, the desktop case. The investigation in parallel of two different catchment characteristics for the same site allows understanding on how catchment characteristics impact on treatment train implementation. The third case study investigated, the Houston Industrial Estate, is an existing industrial area with a strong need for SuDS retrofitting. The methodology presented in Chapter 3 and taking into account the recommendations issued from the Chapter 4 is applied to these three cases studies. Far from being representative of all the potential cases studies where there is need for SuDS, the investigation of these three case studies provide an exhaustive overview of the challenges faced by stakeholders regarding SuDS implementation.

5.1 THE DALMARNOCK ROAD AREA

The Dalmarnock Road Area has been selected for its potential to integrate innovative SuDS techniques while reducing the land take of the planned regional control. This section presents the context in which the Dalmarnock Road area, part of the Clyde Gateway, is investigated before the methodology presented in Chapter 3 is applied. The results issued from the application of the methodology are investigated in terms of their potential impacts on the benchmarks selected in Chapter 3.

5.1.1 THE DALMARNOCK ROAD AREA IN THE CONTEXT OF THE CLYDE GATEWAY

The investigation of the Dalmranock Road Area takes place in the wider context of the redevelopment of the Clyde Gateway situated along the River Clyde in Glasgow. The area, due to welcome the Commonwealth game in 2014, is scheduled to be redeveloped as a high standard residential and business area. The need to regenerate this neglected area as a “sought after” location is paving the way for a forward looking development plan for the area. Following national guidance on the establishment of development plans (Scottish Executive, 2002), the second version of the structure plan for the Glasgow area was adopted on the 7th of December 2009. This structure plan aims to guide future development plans by providing a framework to support decision making. It contains policies and forward looking visions for Glasgow and especially for the Clyde Gateway and the Clyde Waterfront areas where important redevelopments are due to take place (Glasgow City Council, 2009). Following national guidance recommendation to review structure plans at least every 5 years, a third version of the city plan (Glasgow City Council, 2010a) was underway at the time the case study was developed. However, the new version of the structure plan, as it was available at the time of writing (Glasgow City Council, 2010b), does not impact the work undertaken.

Aside from the structure plan, recent flooding in Glasgow and poor watercourse quality led to the development of a forward looking surface water management plan (Aukerman et al., 2008). Preliminary investigations, undertaken by Hyder Consulting, have lead to the production of three main reports (Copty and Adshead, 2007):

- Phase 1 investigated the needs for water management for the Clyde Gateway area in the context of current guidance and legislation;
- Phase 2 investigated potential SuDS schemes along with hydraulic modelling, costs determination and components sizes. The report focused on three main areas, namely Dalmarnock, Shawfield and Farme Cross.
- Phase 3 identifies twelve scheme areas composing the Clyde Gateway. Based on findings of the Phase 2, the report provides key technical data affecting the design of surface water drainage for the different locations. For each area, the report provides a discussion highlighting the more significant issues and proposes possible solutions.

Overall, the three reports give the context within which the case study is formulated and provide some initial material on which the methodology presented in Chapter3 is applied.

The reported project uses a small part of the Clyde Gateway, the Dalmarnock Road Area (Figure 5-1), to apply the methodology presented in Chapter 3. Supporting the structure plan, the local plan for the area (Glasgow City Council, 2008), describes the vision of the strategic objectives to be achieved in redeveloping the Clyde Gateway area. The local plan presents the Dalmarnock Road area as a redevelopment area for residential and businesses development. The north of the area is presented as key in the redevelopment, with the construction of iconic buildings and benefiting from important transport investments. In parallel, the reach along the River Clyde, has been identified as an area with a potential to safeguard biodiversity and provide amenity while providing flood protection and drainage capacity for the area. Based on structure and local plans for the area, Halcrow presented several potential development plans for the Dalmarnock Road area. Both development plans propose higher dwelling densities in the northern part which decrease towards the south. While there are still uncertainties regarding the densities to be adopted, this vision has been adopted as the basis for investigations in this research (Figure 5-1).

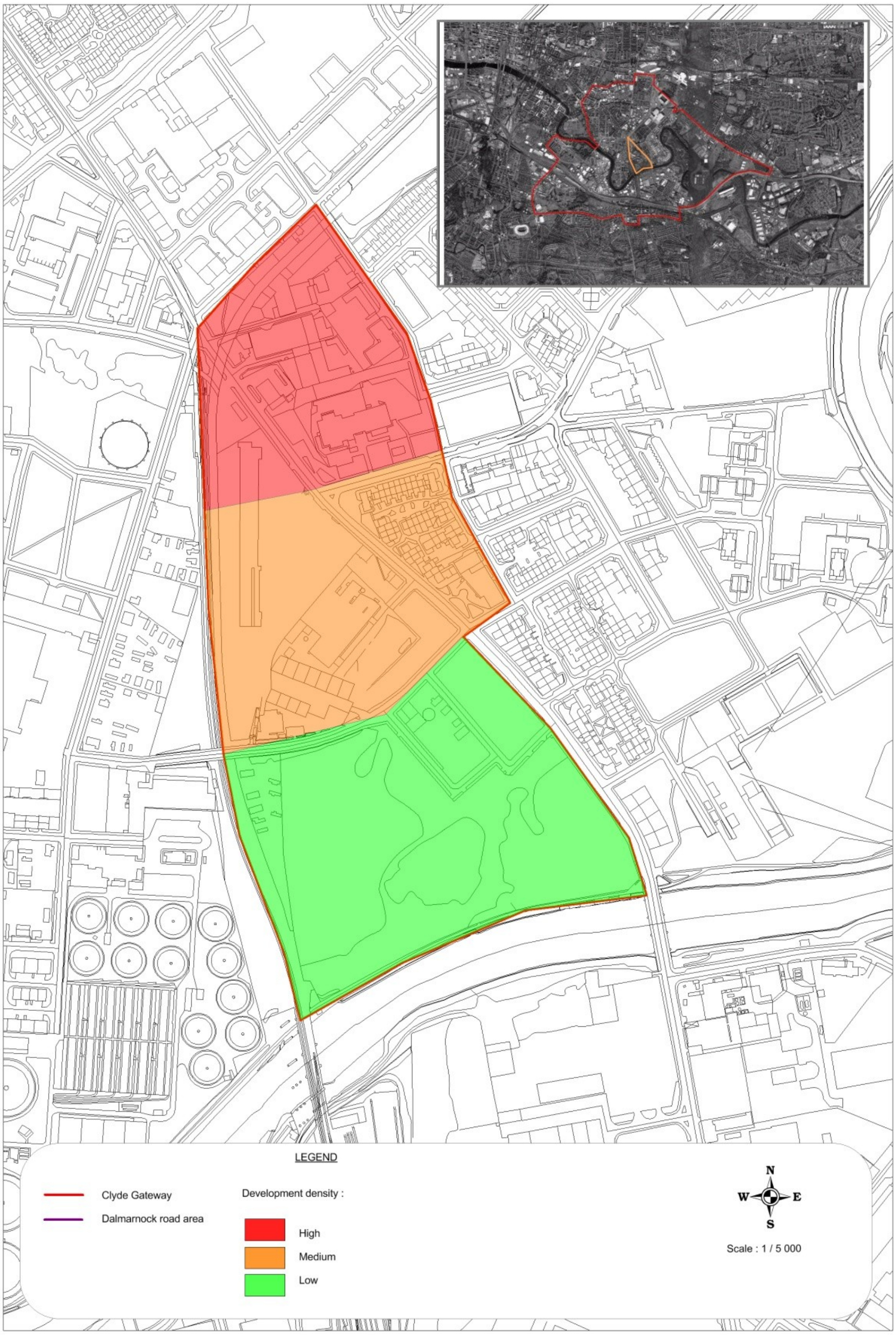


Figure 5-1: Potential development for the Dalmarnock Road Area (Halcrow, 2007)(modified)

From a water quality point of view, the River Clyde has been reported as moderate upstream of the Dalmarnock Area and poor downstream of the Dalmarnock Area according to the SEPA's classification. Intermittent discharges of untreated runoff and foul water from CSO's are responsible for the degradation of the water body. Although the implementation of separate and/or SuDS systems is not feasible for the whole Clyde Gateway area (Copty and Adshead, 2007), they are planned for the Dalmarnock Road area to counter these issues. Early investigations undertaken by Hyder Consulting Limited (2007) state that if no source or site controls are used, a regional pond of 2200m^2 will be required to treat runoff to an acceptable level according to recommendations regarding pond permanent pool design currently in use in Scotland (Section 2.3.3).

From a water quantity point of view, the Clyde Gateway area suffered from a historical event in December 1994 with an estimated return period of 92 years. This event caused severe flooding within the Clyde Gateway with social and economic impacts which have underlined the fragility of the current flood protection (GCC Land services, 1999; Strathclyde Water Services - Sewerage Central Division, 1995). Although the Clyde can be influenced by tides, the Clyde gateway is mostly at risk of fluvial flooding on which surface drainage of runoff impacts. However, with only 8.4km^2 for the Clyde Gateway area, this represents less than 0.5% of the Clyde's 900km^2 catchment. Consequently, the discharges from Clyde Gateway, considering the historical event of December 1994, would only impact by a few centimetres on the level of the Clyde (GCC Land services, 1999; Strathclyde Water Services - Sewerage Central Division, 1995). Consultation with local authorities on this issue and reported in HCL reports (Copty and Adshead, 2007) state that the impact of the Clyde Gateway has not been considered as significant. However, although no decision by local authorities and environmental regulator had be taken, HCL investigated three likely possibilities regarding the return period to be attenuated. Thus, the report considers the three alternatives encompassing three hypothesis: 1) there is no need for attenuation in regards to river regime protection; 2) there is a moderated need for river regime protection and runoff is attenuated to a 30 years return period; and 3) there is a strong need for river regime protection and runoff is attenuated to a 100 years return period. These options will be considered against other hard engineering options (Glasgow City Council, 2007) by local authorities and environmental regulator before final decision regarding the return period to be attenuated is taken. In the case attenuation of a 100 years period is required an additional 2600m^2 will be required (2.5 % of the catchment area).

Interviews conducted with the local authorities as part of the work undertaken to understand SuDS barriers and drivers (Section 3.2.1) have underlined that the land occupied by ponds was seen as a barrier preventing further development taking place. An alternative drainage option, to complement the end-of-pipe pond, has been to deploy a green-blue network link to support sustainable transport in the area (i.e. cycling or walking). This consists in a linear wetland conveying water from the upstream part of the development to downstream regional control facility (Copty and Adshead, 2007; Glasgow City Council, 2008). The green blue link, and other SuDS options could be used to reduce the land take of the regional SuDS control.

Considering the issues and challenges presented, the area was proposed as a case study as a shift towards a different management of urban storm water could be tested. In particular, the development of alternative source and site controls SuDS to reduce the land take of the regional control offers an opportunity to move from the Vt design approach (Section 2.3.3) to the alternative assessment of water quality proposed in Chapter 3. The challenge is therefore to design a pond with a high biodiversity and amenity potential to optimise acceptability to residents (Chapter 4) but with a reduced impact on land take based on water quality benefits provided by source and site controls. The application of the methodology investigates the potential SUDS that could be implemented for the area before assessing their potential impacts on the stakeholders' objectives and barriers presented and defined in Chapter 3. This investigation allows the identification of preferable solutions to be undertaken at an early stage and establishment of water quality-whole life cost-land take relationships for different SuDS treatment trains. These relationships are to be used by stakeholders at a later stage to adopt the best treatment train option.

5.1.2 Selection of potential SuDS techniques (Phase 1) and key design parameters

Due to its heavy industrial past, it is possible that the soil contains several pollutants in sufficient quantities to pose a threat to the groundwater. The precautionary principle prevailing in this case has been adopted by Hyder Consulting while undertaking preliminary investigations for the development of end-of-pipe system for the area by preventing the use of infiltration systems. This view has been adopted while investigating SuDS solutions for the area and constitutes the "realistic" case, the redevelopment of a Brownfield area. However, considering no in-situ investigations have been made for the area and the risk of pollution migration is not confirmed, the infiltration could reasonably be allowed for the area. This situation has also been investigated and constitutes the "theoretical" case study, the development of a Greenfield area. These two cases studies are investigated in parallel so as to understand the impact of different site characteristics.

One characteristic of the work undertaken is that drainage opportunities are assessed early in the development stage. Although good practice, this situation is unusual in that drainage options are usually considered late in the development, often in the last stages before the construction begins. While this situation is a good opportunity to take into account potential SuDS that may not be considered at later stages, it is also a drawback as no accurate development plans for the area have been made available. Based on the available data and although more detailed development plans will be considered in the future, the view adopted in the presented research is that the development of SuDS will be dependent on their land take and their potential amenity in relation with the planned development density for the area (Figure 5-1). SuDS deployment has been considered as follow:

- The northern part of the site will not see above ground SuDS devices unless they are part of the infrastructure such as green roofs or presenting a high amenity potential.
- The central part is more likely to adopt SuDS devices where they present a high amenity, thus improving biodiversity and urban wellbeing according to the findings of the Chapter 4.
- The southern part of the site will be developed at a low density, where the use of lower amenity SuDS is acceptable.

Based on potential land use, site and catchment characteristics, the following key SuDS source, site and regional controls have been considered:

- Linear wetland (LW) or enhanced swale can be implemented in the low density and high density developments to drain the whole area. The linear wetland has been designed as a three meters wide dry swale where the removal of pollutants and potential runoff infiltration take place in a similar way to swales.
- Standard conveyance swales (SW) can be used in the southern part of the site where lower density development is expected. Design is following CIRIA's recommendations (CIRIA, 2007) for dry swales.

- A regional pond (RP) which discharges into the River Clyde is the "default end-of-pipe" solution in the southern part of the site. Design of the regional pond is based on recently published guidance (Scottish-Water, 2007; CIRIA, 2007) aimed at ensuring it captures the first flush for the whole area. The design can also include a volume dedicated to attenuate events up to the 100 year return period level.
- Extensive green roofs (GR) can be used instead of exposed roofs in the north part of the area where large roof surfaces are more likely to exist due to increased density. It should be noted that although the use of intensive green roofs, which offer a higher amenity, would achieve better attenuation (at a greater cost) they have not been considered in the reported research. Literature on the performance of green roofs in terms of attenuation reports a wide range of values depending mostly on the depth of substrate (CIRIA, 2007). Deutsch et al. (2007) recommend assuming the retention of the first 25 mm of each rainfall event. This value is associated with the costs determined by Wong et al. (2003) for the development of an extensive green roof and takes into account potential economies realised on the construction of a conventional roof to determine the whole life cost as a function of the stored volume.
- Concrete block pavement (CBP) can be used where traffic speeds are below 60km.h^{-1}. As such, they can be used in very low density development and on a case-by-case basis in other areas. In this case, their use is concentrated in the areas of low density development. The design of concrete block pavement is usually done on a structural and a hydrologic design, the most restrictive being adopted (Interpave, 2008). The depth of the sub-base is key in these designs as larger depth can accommodate larger loads and also attenuate larger runoff volumes. Based on the limited information available for the site, a sub-base able to accommodate a 30 years design rainfall event has been adopted as the initial design.
- Subsurface storage (SS) can provide attenuation of runoff anywhere it is deployed in the study catchment. A whole life cost-volume relationship has been established based on Duffy et al. (2008):

$$WLC_{SS} = 220.7 \times V + 13259 \qquad (1)$$

Where:

WLC: Whole Life costs (US$)

V: Stored volume (m^3)

- Water butts (WB) can be used in low density development to store and reuse water for gardening purposes. The adopted design is of a water butt satisfying both water storage and water attenuation purposes. The water storage volume is not taken into account in the evaluation of the potential attenuation according to the risks of this storage being full at the beginning of the storm event (Section 2.2.3.4). The additional storage designed for attenuation has been fixed to $0.3m^3$ per dwelling.
- Soakaways (SO) can be used in low density development to infiltrate roof runoff. These are designed to store and infiltrate runoff of 30 years return period events.
- Infiltration trenches (IT) can be used in medium density areas to drain road pavements. Infiltrations trenches are designed to store and infiltrate 30 years return period events.

The use of these SuDS is considered differently, depending on the conditions considered for the soil and the impact of potential infiltration. Some of the techniques can be used in both cases provided that a liner prevents the infiltration into the soil where it is necessary. Overall, logical combinations of the different SuDS devices allow consideration of 23 different treatment trains comprising one to six SuDS that can be assessed for water quality performance in case infiltration is prevented. If infiltration is permitted, logical combinations of the different SuDS devices allow consideration of 19 different treatment trains comprising one to five SuDS.

5.1.3 Assessment (Phase 2)

The section below details the application of the methodology presented in Chapter 3. The assessment provides an evaluation of three quantitative benchmarks that can be readily considerd at the design stage. It is worth noting that although these quantitative benchmarks are used to evaluate the main barriers and drivers for SuDS implementation, they do not take into account quantitative benefits that may arise as by-products of the treatment train implementation. This is notably the case for the potential amenity and biodiversity that may arise, which mainly on pond design and maintenance as demonstrated in Chapter 4. These added benefits are difficult to characterise, especially at the design stage and will hence not be considered further.

5.1.3.1 Pollutant percentage removal

Section 2.4.3 reviewed the notion of a treatment volume currently in use and how it was derived from the willingness to treat around 90% of the rainfall events by capturing an equivalent volume. For the Dalmarnock Road Area, this volume corresponds to the equivalent of 12 mm of rainfall across the catchment. The notion of captured volume is no longer valid if SuDS, not incorporating a permanent pool are used and a shift from the notion of captured volume had hence to be proposed. Since the objectives are to treat 90% of the rainfall events, a Time Series Rainfall (TSR) for the area would have been desirable. However, to simplify the assessment of the research hypothesis, a M5-60 event corresponding to 12mm of runoff has been chosen as a benchmark for water quality assessment.

A water quality model for the area has been developed using MUSIC (presented in Section 2.3.1.1). The software has been used to perform water quality comparisons for different treatment trains based on the removal of TSS, TP and TN.

The software is a hydrological and hydraulic model which allows the conceptual representation of catchments and SuDS. The latter are represented under the form of source and treatment nodes linked together through drainage links.

For source nodes, representing a subcatchment draining to a treatment node, the user specifies catchment characteristics necessary for the software to perform hydrological calculations. The characteristics include subcatchment area, percentage of imperviousness and mean percentage concentrations. In the absence of onsite measurements of pollutants concentrations for the area, pollutant concentrations have been sourced from literature. Monitoring of pollutants generated by different land uses (Duncan, 1999; Gobel et al., 2007; Mitchell, 2005) has shown a certain consistency in the amount of pollutants that can be expected for different land uses. Within this context, the estimated pollutant concentrations for total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP) can be found in Table 5-1. In most residential areas, roads are the main source of suspended solids and they are associated with major pollutants such as PAHs, oil and heavy metals.

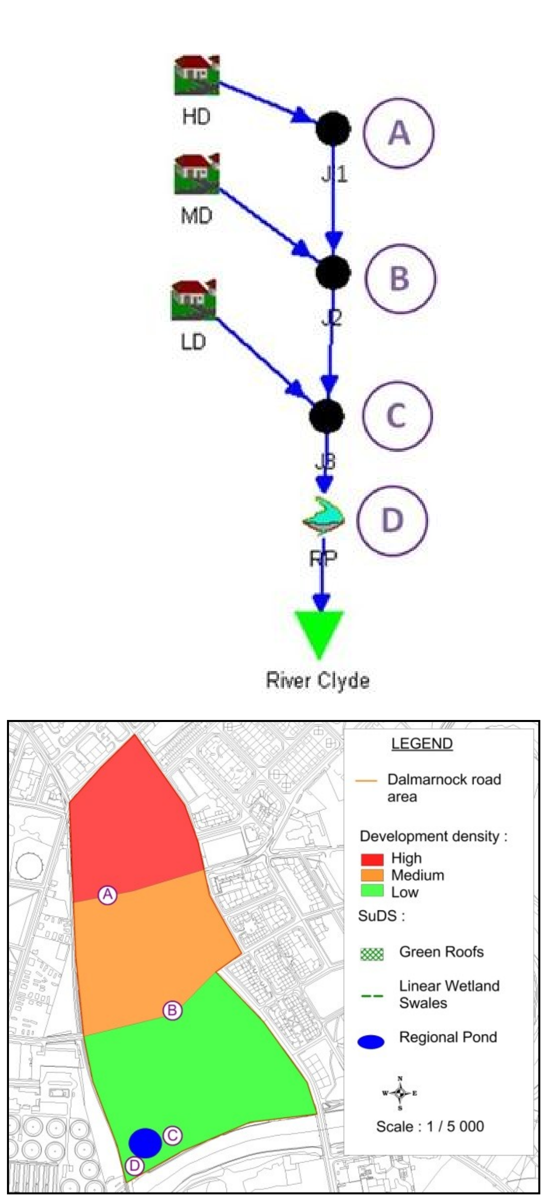
	Concentrations ($mg.l^{-1}$)		
	Residential development	Roofs	Roads
TSS	160	35	281
TP	0.35	0.15	0.56
TN	2.63	0.53	4.68

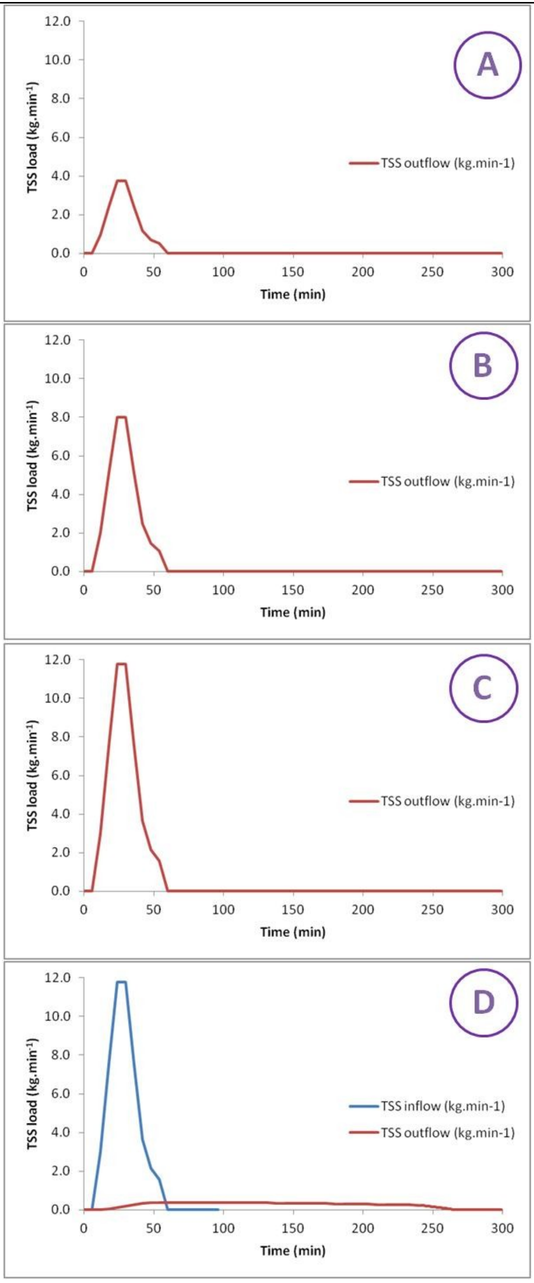
Table 5-1: Expected pollutant concentrations for a residential development (USEPA, 1983)

Treatment nodes are used to represent different SuDS and model their hydraulic and water quality performance. The software includes a range of default SuDS including wetlands, ponds, swales, infiltrations systems and rainwater tanks for which the user specifies the technical characteristics which have an impact on hydraulic and water treatment performance. For example, the specifications for a pond include the depth and volume of the permanent pool, the surface area and the diameter of the orifice outlet. For a swale, the user specifies the length, the base and the top width, the depth and the vegetation height. The geometrical specifications are then used by the software to determine hydraulic performance including the detention time and the hydraulic loading for all the SuDS considered. Based on hydraulic loading, water quality performance is then determined using first order decay parameters (Section 2.5.2.1.1) for which the software provides default values derived from the sedimentation equation (Fair, 1954) and confirmed through calibration surveys (Wong, 2006).

The representation of multiple SuDS can, in some cases be modelled as a single treatment node. For example, this is the case for green roofs which may be represented as a single storage node draining the roof area of the high density part of the development. In this case, green roofs are represented as a single storage node of 265 m^3 corresponding to the storage of the first 10 mm of rainfall over the 2.65 ha estimated surfaces of roofs. Notwithstanding, this approach cannot be implemented for linear structures such as swales or infiltration trenches. Indeed, following recommendations (CIRIA, 2007), these SuDS are generally not designed for point source inflow but for distributed inflows. In order to model distributed inflow, the source and treatment nodes are discretized. In the modelling source nodes do not exceed the size of 0.5 ha while treatment nodes do not exceed 50m long. The different treatment nodes are then linked together.

The different treatment trains possibilities identified in Section 5.1.2 have each been modelled using MUSIC. While global outputs are presented latter, the section below presents the modelling and intermediate results of three key treatments trains.

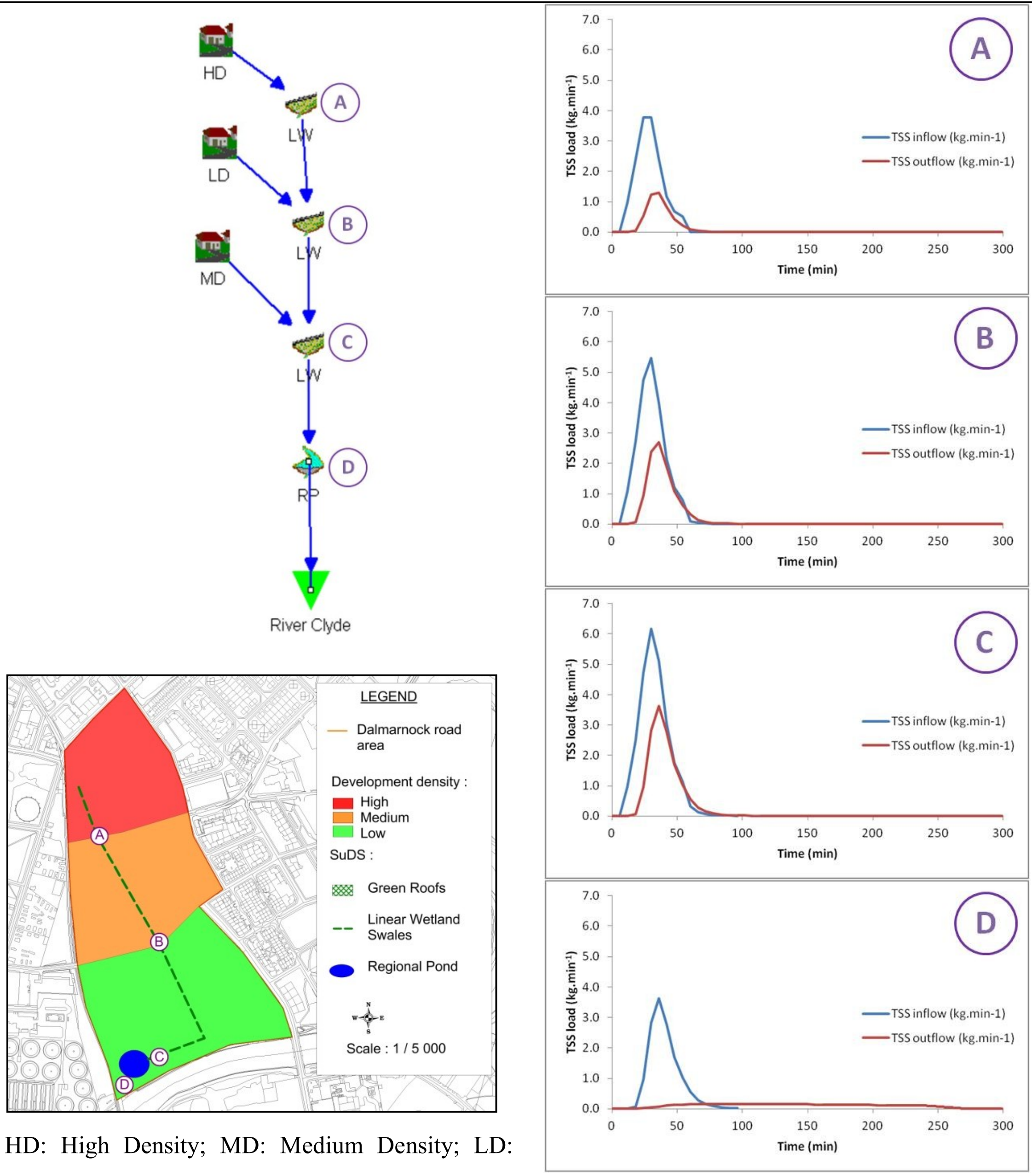




HD: High Density; MD: Medium Density; LD: Low Density; J1, J2, J3: Junction nodes

RP: Regional Pond

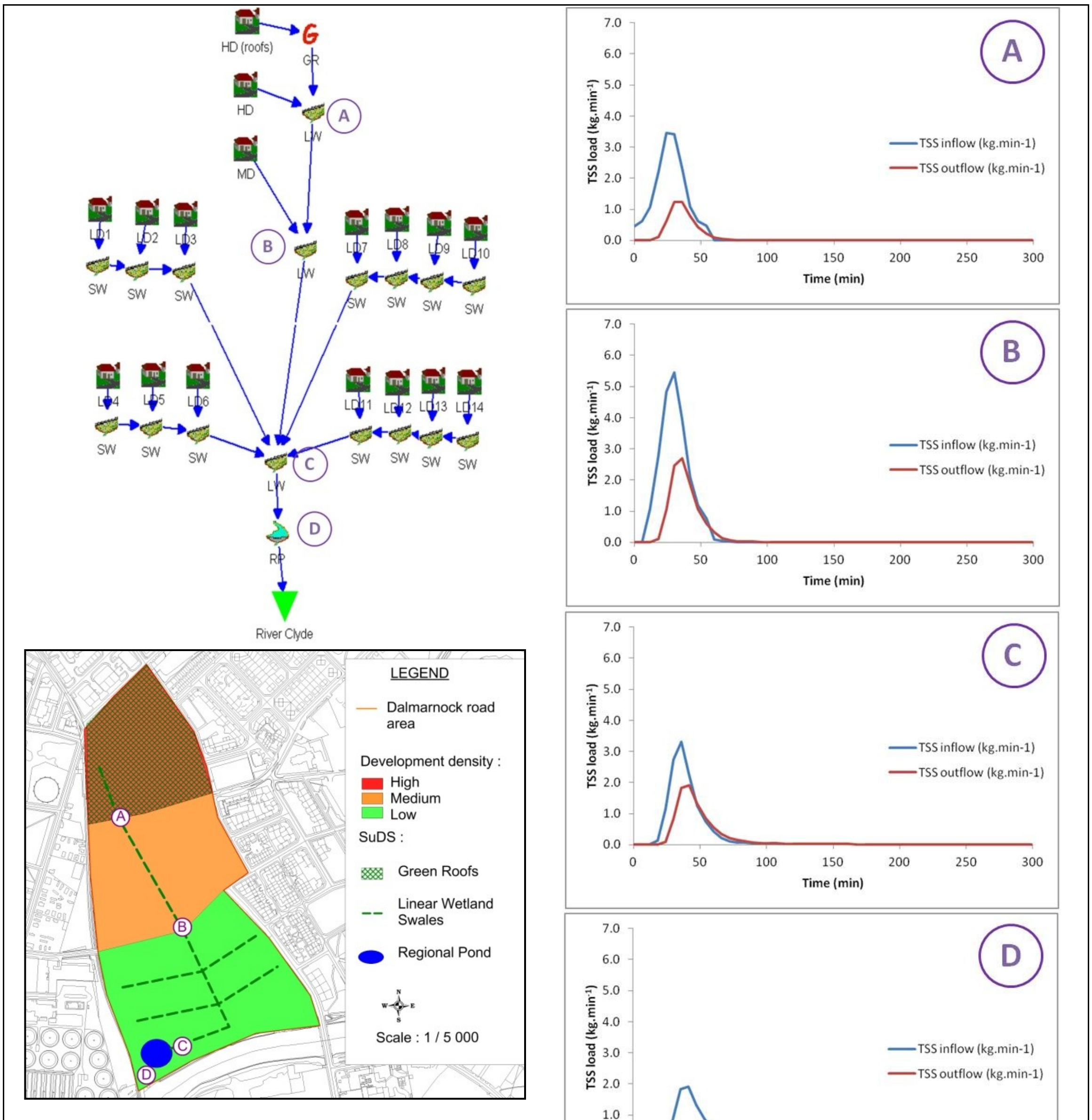
Figure 5-2: Modelling of a treatment train containing a single regional pond using MUSIC



HD: High Density; MD: Medium Density; LD: Low Density;

RP: Regional Pond; LW: Linear Wetland

Figure 5-3: Modelling of a treatment train containing a linear wetland using MUSIC



HD: High Density: MD: Medium Density; LD: Low Density;

RP: Regional Pond; SW: Swales

Figure 5-4: Modelling of a treatment train containing green roofs, a linear wetland and swales using MUSIC

Total Suspended Solids (TSS)		Treatment trains		
		Regional Pond	Regional Pond, Linear wetland	Regional Pond, Linear Wetland, Swales and Green roofs
A	Maximum peak load discharged ($kg.min^{-1}$)	4.0	1.5	1.2
	Total load discharged (kg)	16	5	4
	Global removal (%)	0%	69%	75%
B	Maximum peak load discharged ($kg.min^{-1}$)	8.0	2.5	2.3
	Total load discharged (kg)	33	11	10
	Global removal (%)	0%	67%	70%
C	Maximum peak load discharged ($kg.min^{-1}$)	12.0	3.7	2.0
	Total load discharged (kg)	49	15	9
	Global removal (%)	0%	69%	82%
D	Maximum peak load discharged ($kg.min^{-1}$)	0.3	0.2	0.1
	Total load discharged (kg)	15	7	5
	Global removal (%)	69%	86%	90%

Table 5-2: Spatial evolution of TSS load and concentration for the three key treatment trains

The Figure 5-2 to Figure 5-4 completed by Table 5-2 shows how the concentration of suspended solids evolves from upstream to downstream. In the case where only a regional pond is used, maximum peak loads and total loads are gradually increasing before entering the regional control, where a global removal of TSS only achieves 69%. In the case where upstream source controls are used, the peak loads and total loads discharged are reduced along the treatment train. The maximum of this reduction is achieved for the third treatment train, presenting the largest source and site SuDS deployment.

5.1.3.2 **Whole life costs**

The determination of the whole life costs for the area considered takes place within the context of the redevelopment of brownfield and greenfield areas. Although drainage infrastructure is present on the site, it is based on a combined system with an unknown capacity. As the area will be completely redeveloped, it is unlikely that the present infrastructure to drain water will be reused; especially considering a separate pipe network will be implemented for the area. Consequently, adopting this point of view, the whole life costs considered are those associated with the development of the full infrastructure draining surface runoff from the catchment. This allows a holistic approach to SuDS implementation and discusses possible optimisation of cost recovery between the stakeholders.

As discussed in Section 3.2.2.2, the determination of the drainage system whole life costs based on reported values would be a difficult exercise considering the lack of reported data in the literature for several of the SuDS devices presented in Section 2.2.3. Consequently, the costs have been determined using the bill of quantities methodology presented in Section 2.5.3. According to the findings of Chapter 4 which underlined that well maintained SuDS are more likely to be acceptable to residents, the determination of the Whole Life Costs assumes high maintenance standards for the devices considered. Table 5-3 summarises maintenance routine for the SuDS.

	Maintenance activities	Frequency (months)
Regional pond (UKWIR, 2005)	Inspection, reporting and info management	1
	Litter and minor debris removal	1
	Grass cutting	4
	Barrier vegetation weeding	12
	Aquatic vegetation management	12
	Algae removal	4
	Barrier vegetation pruning	36
	Sediment removal from engineered silt trap	6
	Sediment removal from forebay	36
	Sediment removal from the pond	120
	Vegetation replacement	300
	Removal and disposal of construction sediments	once after 12 months
Swale (UKWIR, 2005)	Inspection, reporting and info management	1
	Litter and minor debris removal	1
	Vegetation replacement	300
	Removal and disposal of construction sediments	once after 12 months
Linear wetland (UKWIR, 2005)	Grass cutting	1
	Sediment removal	120
Sub-surface storage (Duff, 2008)	Grass cutting	1.5
	Litter removal	1.5
	Inspection of structures	6

	Desilt inlets & outlets	12
	Controlled disposal / Haulage of silt	120
	Remove blockages	120
	Jetting	120
	Repair broken components	120
	Controlled disposal / Haulage of silt	120
	Remove blockages	120
	Jetting	120
	Repair broken components	120
Concrete block pavement (Scholz, 2007; UKWIR, 2005)	Inspection, reporting and info management	1
	Litter and minor debris removal	1.5
	Permeable pavement sweeping	4
	Remove block paves and stockpile to be washed	300
	Install replacement geotextile, install new 5mm single aggregate bedding layer and reinstate block.	300
Green roofs (Wong, 2003)	Inspection of drainage system	6
	Replacement of waterproofing membrane	480
	Water and weed of the turf / replacement if necessary	0.5
Infiltration trenches (UKWIR, 2003)	Inspection, reporting and info management	3
	Litter and minor debris removal	2
	Grass cutting	1
	Sediment removal from engineered silt trap	6
	Sediment removal from the filter drain (total cost)	120
Soakaways (BRE, 1991; Stovin, 2007; Swan 2002)	-	-
Water butts (Stovin, 2007; Swan 2002)	-	-
Infrastuctures	Maintenance activities	Frequency (months)
Exposed roofs (Wong, 2003)	Inspection of drainage system	6
	Replacement of waterproofing membrane	120
Asphalt pavement (Interpave, 2006)	Inspection of drainage system	120
	Surface course replacement	240
	surface course repairs on 6% of the surface	240
	Surface dressing	once after 120 months, then every 60 months
Excavation and full reinstatement on 0,5% of the surface	240	

Pipe network (Scottish-Water, 2007; Langdon, 2009)	-	-

Table 5-3: Maintenance frequency for the SuDS considered.

The situation in Scotland at the time of investigation is that the use of separate systems to convey foul water and runoff water independently is compulsory for all new developments under the WEWS act (Stationery office, 2003). Foul water is treated at the local Waste Water Treatment Plant (WWTP) while runoff is discharged in the natural environment. This legislation has been reinforced under the Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR) (Stationery office, 2005) stating that virtually all runoff from areas constructed after the 1st April 2007 must be drained by at least one SuDS (Section 2.3.2.). The Dalmarnock Road area is no exception to this rule and the work undertaken confirmed, despite some uncertainties regarding the extent and the design, that separate system and SuDS are due to be incorporated in this new development. These new regulations represent a shift in the way costs should be assessed. While the establishment of costs by comparison with the development of a combined system have been used before the legislation come into force, this comparison is no longer valid considering the development of a SuDS system is now the norm. The point of view adopted in this research is that the cost of implementing SuDS is made by comparison with the implementation of a separate system only. This point of view explains that the situation of reference to which the treatment trains are evaluated and compared is the development of a separate pipe system. In regards to the reference situation, the costs are considered as a difference from this initial situation where a single end-of-pipe pond is developed. This situation impacts significantly on cost estimation for some of the SuDS devices. For example, the whole life cost of a drainage network using swales is determined by subtracting the costs of the pipe network that would be developed instead. Also, this approach leads to consideration of the fact that maintenance over the whole life of the project could be significantly different depending the SuDS developed. In particular, the use of permeable pavement supposes higher maintenance requirements than traditional impermeable surfaces to maintain their water quality and hydraulic performance.

5.1.3.3 **Attenuation volume**

The likely developments presented Figure 5-1 have been associated with the ground model furnished by Hyder Consulting Limited to develop a hydraulic model for the area. The hydraulic model uses the functions provided by Infoworks to model either the attenuation or the infiltration following the characteristics adopted for the SUDS and presented in Section 2.2.3.2. A geological survey for the area reported that superficial deposits are made of alluvial deposits of silt, peat, clay, sand and gravel while made ground deposits have been reported on the western part of the site (Copty and Adshead, 2007). It is likely that some other parts would also be made ground and further investigations would be required to determine the precise nature of the soil as well as the infiltration rate. In the absence of infiltration test data for the area a hypothetical 12mm.h^{-1} has been assumed. This assumption is realistic when compared to the range of typical infiltration rates for this type of geology (Section 2.2.3.2).

5.1.4 RESULTS (PHASE 3)

The section below presents the results of the assessment of the different treatment train possibilities for the Dalmarnock Road Area.

5.1.4.1 Preliminary results

Based on the data determined for each SuDS device, assessment of the different treatment trains, corresponding to different combinations of SuDS devices for water quality performance, land take and costs are illustrated in Figure 5-5, Figure 5-6 and Figure 5-7.

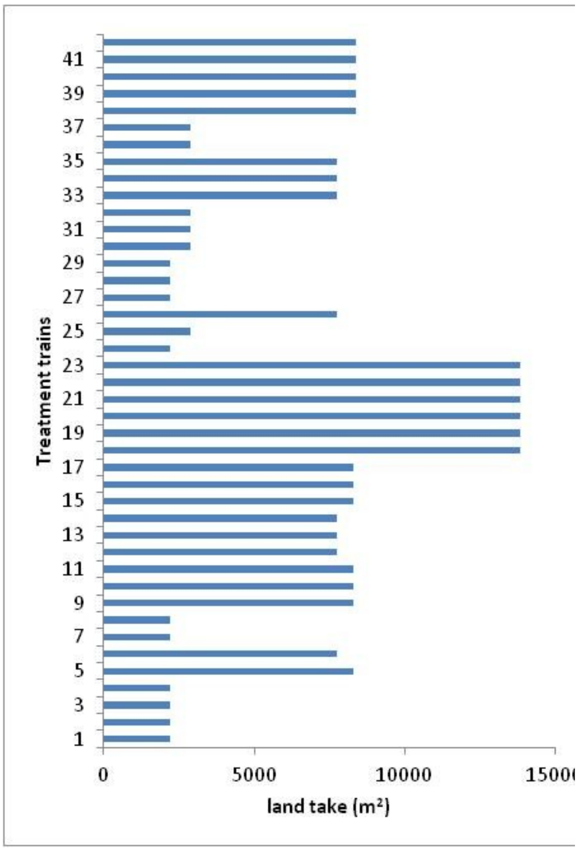


Figure 5-5: Land take for different treatment trains

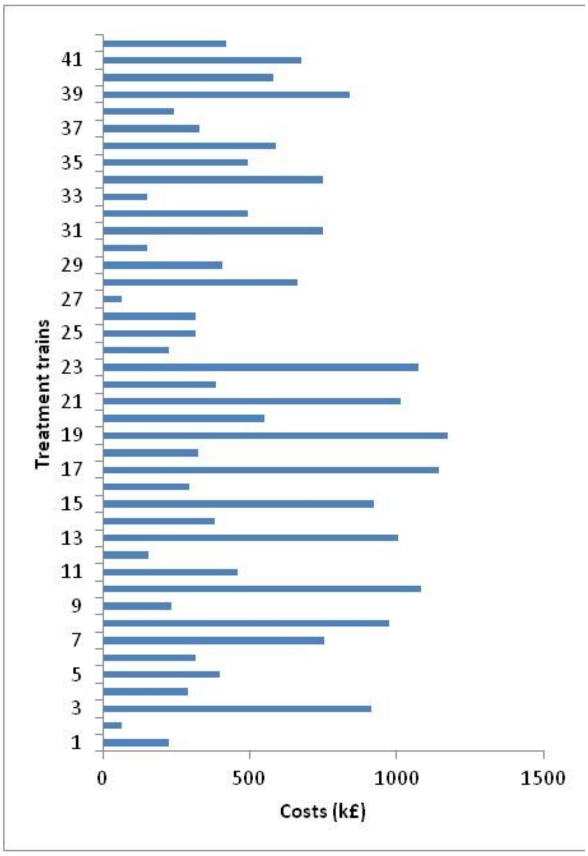


Figure 5-6: Whole Life Costs or different treatment trains

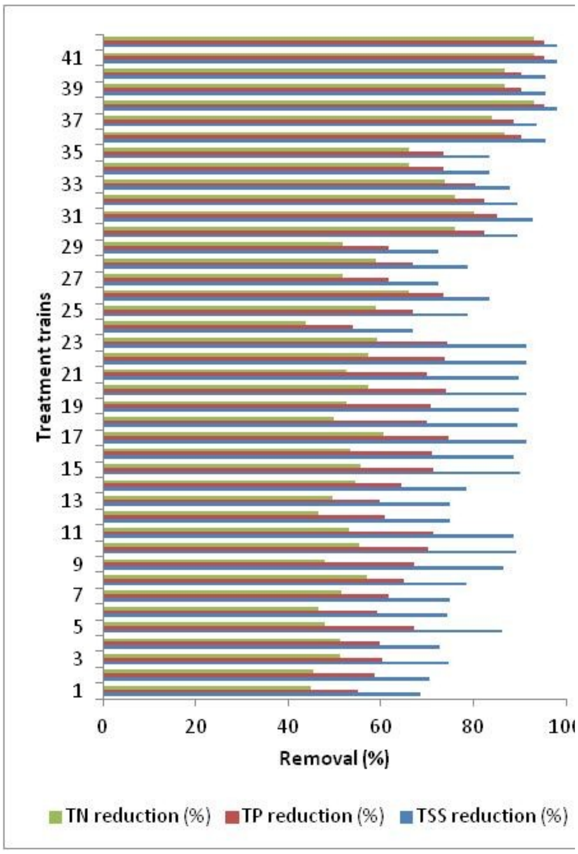


Figure 5-7: Water quality performances for different treatment trains

1*	RP
2*	RP GR
3*	RP CBP
4*	RP WB
5*	RP LW
6*	RP SW
7*	RP CBP GR
8*	RP CBP WB
9*	RP LW GR
10*	RP LW CBP
11*	RP LW WB
12*	RP SW GR
13*	RP SW CBP
14*	RP SW WB
15*	RP LW GR CBP
16*	RP LW GR WB
17*	RP LW CBP WB
18*	RP SW LW GR
19*	RP SW LW CBP
20*	RP SW LW WB
21*	RP SW LW GR CBP
22*	RP SW LW GR WB
23*	RP SW LW GR CBP
24	RP
25	RP IT
26	RP SW
27	RP GR
28	RP CBP
29	RP SO
30	RP IT GR
31	RP IT CBP
32	RP IT SO
33	RP SW GR
34	RP SW CBP
35	RP SW SO
36	RP IT GR CBP
37	RP IT GR SO
38	RP SW IT GR
39	RP SW IT CBP
40	RP SW IT SO
41	RP SW IT GR CBP
42	RP SW IT GR SO

With:

CBP: Concrete block pavement

GR: Green roof

IT: Infiltration trenches

LW: Linear wetland

RP: Regional pond

SO: Soakaway

SW: Swales

WB: Water butts

* The techniques used for these treatment trains are designed to prevent infiltration

As illustrated in Figure 5-3, the use of several SuDS in series tends to increase drastically the land take associated with SuDS. From an initial land take of 2200m^2 for a regional pond, the land take can reach over 14000m^2 if all of the feasible techniques selected during the first phase are to be used. However, the increase in land take varies from one technique to another with some techniques having no impact, the case for green roofs and concrete block pavements, while some others add significantly to the overall land take of the treatment train, the case for the swale network and the linear wetland.

Regarding the whole life costs of SuDS treatment trains on Figure 5-6, the final costs over a 50 years period are very different from one treatment train to another. This situation can be explained by the fact that 1) whole life costs are highly variable from one technique to another, with swales and linear wetlands comparatively cheaper than the installation of concrete block pavement ; 2) the implementation of some devices, although initially expensive, yields significant benefits. This is particularly true for green roofs which are beneficial in the long term according to the calculations of the whole life costs following the methodology presented in Section 2.5.3. This view is supported by several authors (Carter and Andrew, 2008; Acks, 2006) and is based on the theoretical assumption that the choice of a low maintenance vegetation associated with an extended lifespan can offset the construction and maintenance of an exposed roof. The longer term benefits may be reinforced by evaluating the extent to which green roofs provide better insulation and reduce heating and cooling costs (Carter and Andrew, 2008; Wong et al., 2003). Overall, the design of SuDS to prevent infiltration has a limited impact on the overall cost (e.g. the lining of a swale to prevent infiltration only increases the whole life cost by 4%). As a result, the water quality and cost relationship are of a similar order of magnitude for the realistic and desktop cases studies.

As illustrated in Figure 5-7, by using SuDS in series, significant benefits in terms of water quality can be achieved. From a basic removal of 68% of TSS for a single regional pond, the removal can reach more than 90% when several SuDS in series are used. By increasing the removal of TSS, the removal of small particles is improved, thus improving the treatment for heavy metals and PAHs as these pollutants are more likely to be bound to the small particle size fraction of TSS (Lee et al., 2005). Infiltration of TP and TN at source control level increase the overall removal for these pollutants to 95% and 93% removal for TP and TN respectively (in comparison with a maximum removal of 75% and 60% removal for site control TP and TN respectively). This result is due to the removal processes associated with source and site controls, mostly based on the filtration either by substrate or vegetation: these processes have a relatively low impact on the removal of TN and TP which is mostly found in dissolved form (Taylor et al., 2005).

Overall, this section confirms the main stakeholder fears (e.g. whole life costs and land take) regarding the use of SuDS treatment trains rather than using only a single regional SuDS. Although the improvement in water quality is desirable, the whole life costs associated with the different treatment trains show that using multiple SuDS source and site controls has a significant cost impact and land take impacts in most cases.

5.1.4.2 Cost, land take and water quality performance relationships

The previous section has underlined that different source and site controls, while providing water quality and quantity benefits, impact differently on costs and land take associated with the project. Based on the results outlined thus far, it is possible to consider how different attenuation and water quality improvement levels impact on both cost and land take. This is illustrated on Figure 5-8 to Figure 5-16**Erreur ! Source du renvoi introuvable.**, **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.** where water quality and quantity improvements are considered for different attenuation scenarios. The attenuation for these scenarios can either be provided by the regional control, thus increasing the land take, or using sub-surface storage as defined in Section 2.2.3.4, thus increasing the costs. The land take associated with the storage of 30 and 100 year return period events in addition to the land take of the permanent pool is respectively of 4363m^2 and 4788 m^2 for respective volumes of 5560m^3 and 7220m^3. Reduction of volumes reaching the regional control through the use of source and site control help reduce land occupied by the regional control.

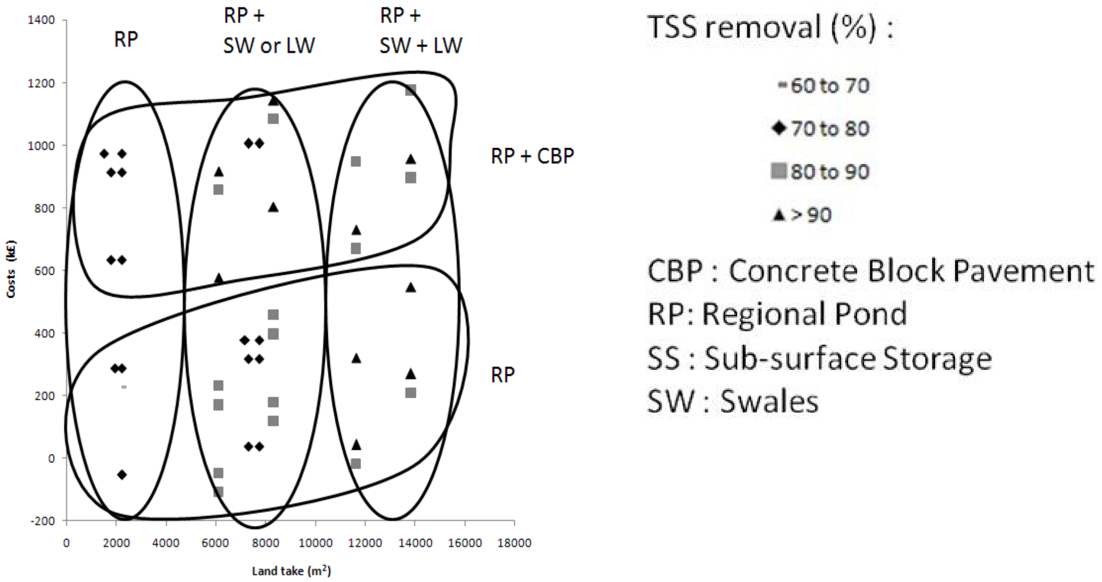


Figure 5-8: Cost size attenuation relationship when no infiltration is required and infiltration is prevented

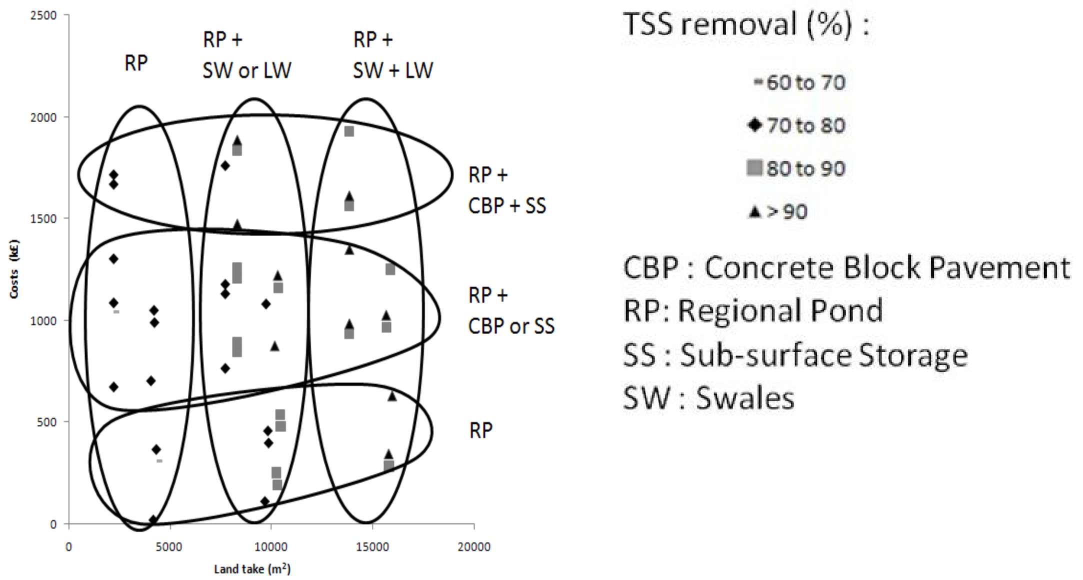


Figure 5-9: Cost size attenuation relationship with 30 years attenuation and infiltration is prevented

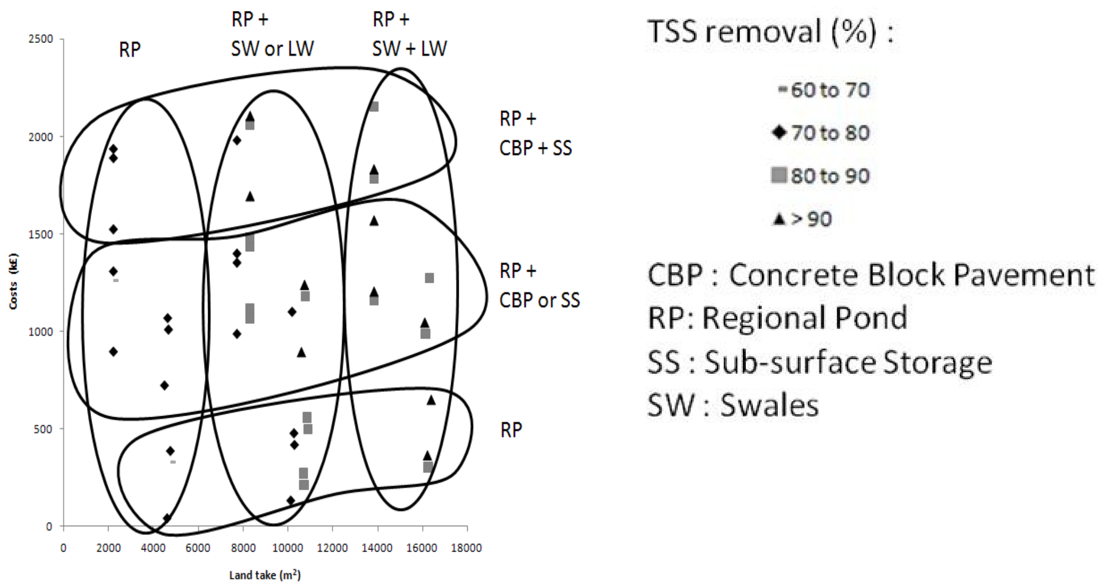


Figure 5-10 : Costs size attenuation relationship with 100 years attenuation and infiltration is prevented

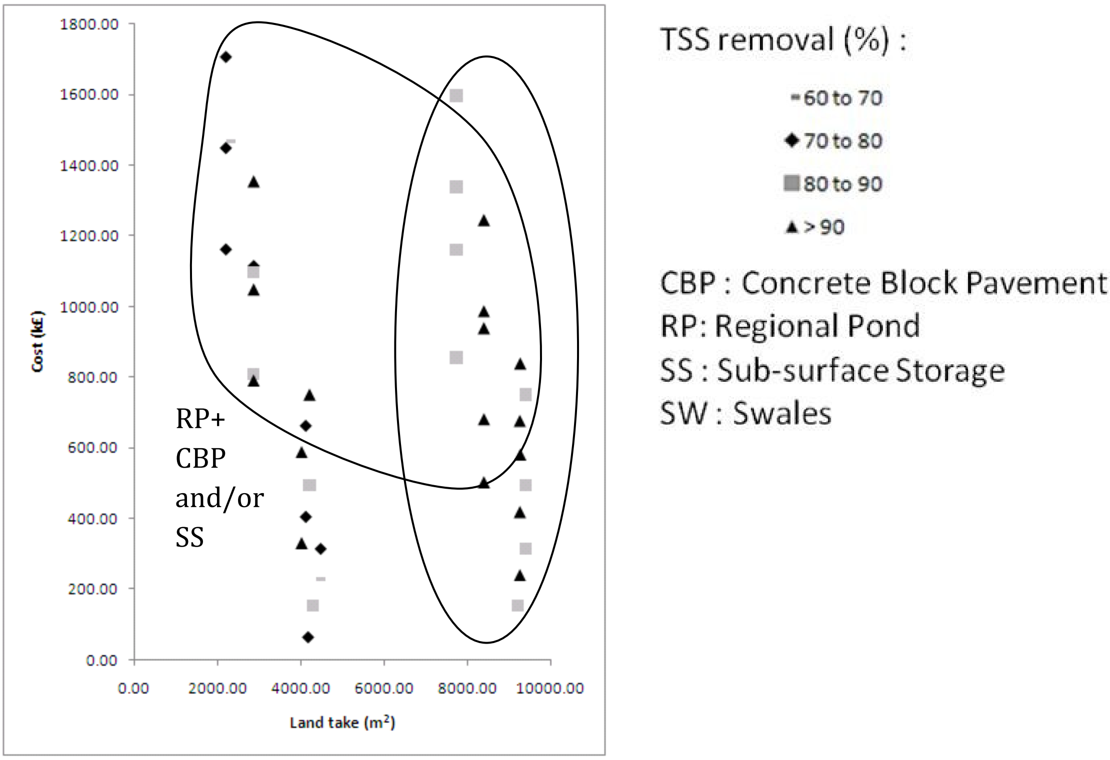


Figure 5-11: Cost size attenuation relationship with 30 years attenuation and infiltration is allowed

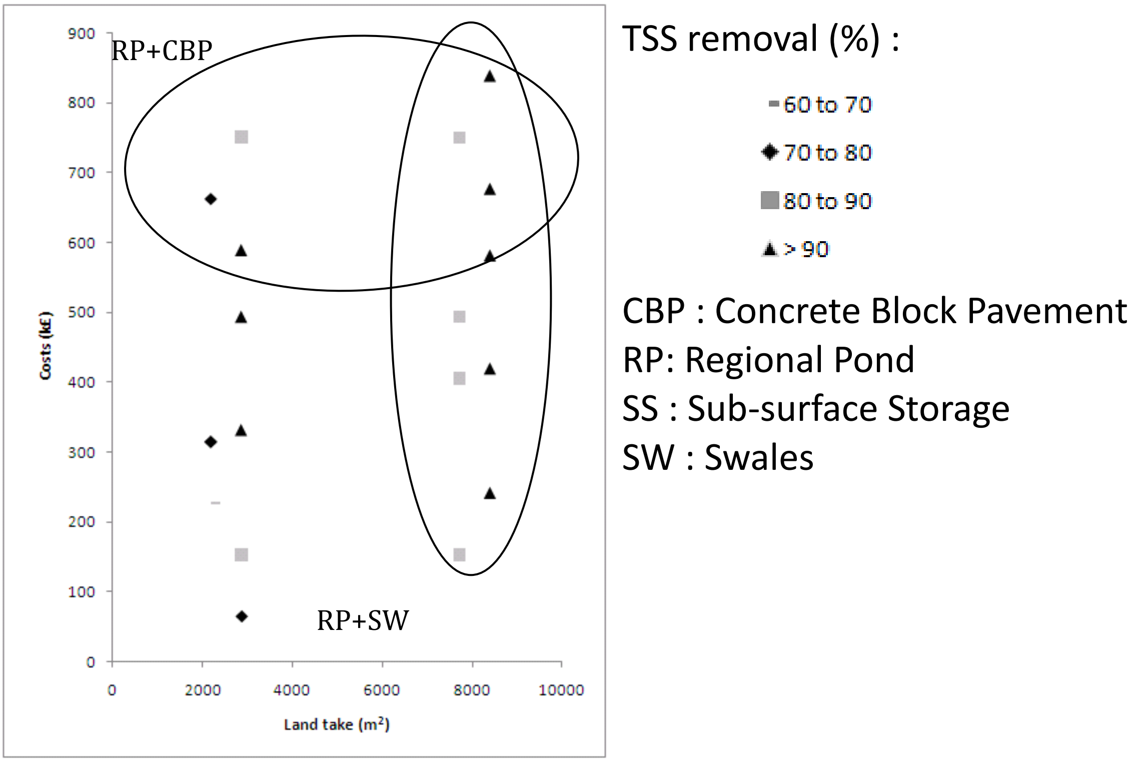


Figure 5-12: Cost size attenuation relationship when no attenuation is required and infiltration allowed

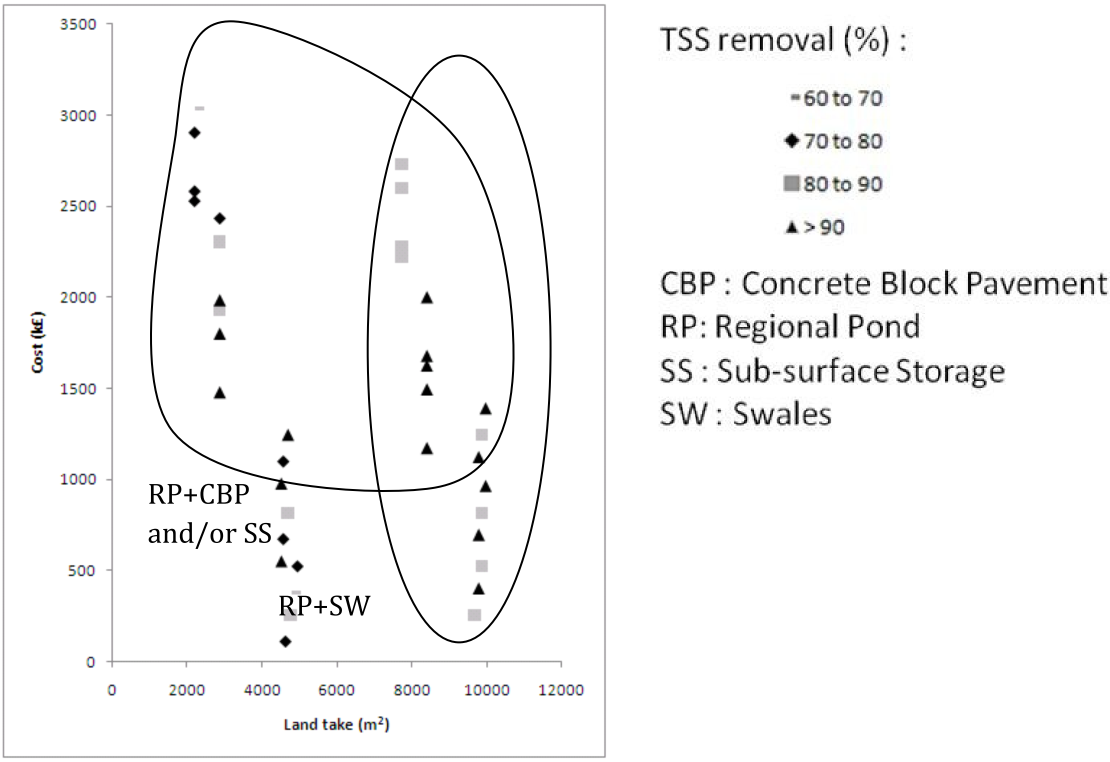


Figure 5-13: Cost size attenuation relationship with 100 years attenuation and infiltration is allowed

The presented figures allow the identification of the main trends affecting land take and costs. These trends have been highlighted on the different plots by circling the treatment trains containing identical SuDS. For example, on Figure 5-9, the treatment trains incorporating a linear wetland or a swale network have greater footprint that any other treatment train. Similarly, the treatment trains incorporating Concrete Block Pavement and/or Sub-surface Storage are more expansive than treatment trains not incorporating one.

Considering the Figure 5-8**Erreur ! Source du renvoi introuvable.**, **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.** significant water quality improvements can be obtained compared to the initial solution using an end-of-pipe pond: the initial removal rate, below 70% for TSS can be improved beyond 90% by either:

- implementing a swale network and a linear wetland; or,
- by using pervious pavement in the low density area in conjunction with the implementation of the swale network or the linear wetland.

The first solution presents the advantage of managing costs efficiently, whereas the second solution offers the opportunity to reduce the land take for an equivalent water quality improvement. For these specific solutions, a land take reduction of 5500m^2 can be achieved for an equivalent cost of ~ £250k. A further 2000m^2 to 2400m^2 are necessary to attenuate the 30 and the 100 year return periods respectively. In addition to the reduction in land take achievable based on water quality benefits of source and site controls, a further land take reduction can be achieved by using subsurface storage to attenuate water quantity to the required standards. Thus, a maximum reduction of land take for a TSS removal rate beyond 90% can be achieved by the use of a swale network or a linear wetland in association with concrete block pavement and sub-surface storage.

Although the costs considered are different due to the simplification of some techniques to infiltrate the runoff, similar observations can be made from Figure 5-11, Figure 5-12 and Figure 5-13: the increase in costs are mainly driven by the use of concrete blocks pavement and sub-surface storage while the use of swales increase the overall land take of the treatment train.

On the presented solutions, some major water quality and quantity improvements can be made without impacting significantly on land take or costs. These treatment trains are normally incorporating the use of green roofs, having a beneficial cost impact on the long term, associated with some other techniques. This is illustrated Figure 5-11 where the use of green roofs in the high density area coupled with infiltration trenches in the medium density area and soakaways in the low density area achieve a high water quality performance while costs and land take are maintained close to those of the initial project. This situation has been rendered possible to the beneficial costs of the green roofs associated with the relatively low costs of the other associated techniques.

5.1.4.3 Proposition to reduce regional control size

The interviews with local authorities reported in Section 3.1 highlighted the inconvenience that presence of the regional control can have on future development of an area and this consideration could markedly affect the level of attenuation provided by the regional SuDS control. Logic would suggest that a reduction in land take can be achieved by optimising the design of the upstream treatment train.

Indeed, pond performance is largely driven by pond surface area (Wu et al., 1996). Consequently, reducing pond surface area will reduce pollutant removal by increasing the hydraulic loading. As shown in Figure 5-7, the use of a single pond achieves a theoretical 68% removal of suspended solids equivalent to a discharge with a concentration of $51.2 mg.l^{-1}$. If this concentration is considered adequate, then if the treatment train produces a level of treatment beyond that level, it follows that the regional pond may be reduced in size until the target performance is reached.

Figure 5-14, Figure 5-15, Figure 5-16 and Figure 5-17 illustrate the achievable land take reduction of regional controls based on water quality and quantity benefits of upstream controls for different return periods. The addition of source and site controls upstream in the treatment train can result in significant benefits in terms of reduction of the regional control, achieving a potential overall reduction of 100% when no attenuation or a limited attenuation is required. Similarly, an overall reduction up to 95% is achievable in the case robust attenuation is desirable.

However, in the case where the regional control appears to be unnecessary because of the upstream treatment train benefits, this solution may not be acceptable for three reasons:

- The pond is the last control before the runoff is discharged and it could be considered as security in case source and site controls do not perform to the required standards.
- More importantly, it should be noted that if better treatment and degradation could be achieved upstream for suspended solids (and bound pollutants such as heavy metal and PAH's), the reduction of treatment volume reduces the opportunity to degrade dissolved pollutants (Taylor, 2005).
- The amenity and the biodiversity that the regional control could propose for the area would be reduced, thus loosing the potential additional value (Chapter 4).

For similar techniques, the infiltration of runoff by source and site controls achieves a significantly higher reduction of the regional control volume. This can be explained by the fact that 1) the infiltrated volume does not need to be attenuated further downstream, and 2) source and sites control devices usually infiltrate the first 12 mm of runoff without discharging and thus no pollutants reach the regional control, thus facilitating a further reduction of the regional control.

However, the achieved reduced land take of the regional control should be placed in the wider context of the treatment train land take. As illustrated in Figure 5-17, in most cases, the reduced land take of the regional control does not compensate for the land used by upstream source and site controls unless these are part of the infrastructure (e.g. CBP). Although the reduction of the regional control land take is constrained by increases in land take in most of the cases and this may be viewed as a disadvantage, it may be considered by the developer as an alternative way to spatially manage the SuDS footprint. An example of this is the land take associated with swales: their position along the roads may make them more acceptable than setting aside a large area for a regional pond. This aspect is discussed in Chapter 6 where the presented framework consider the value associated to land take and how this could impede further development.

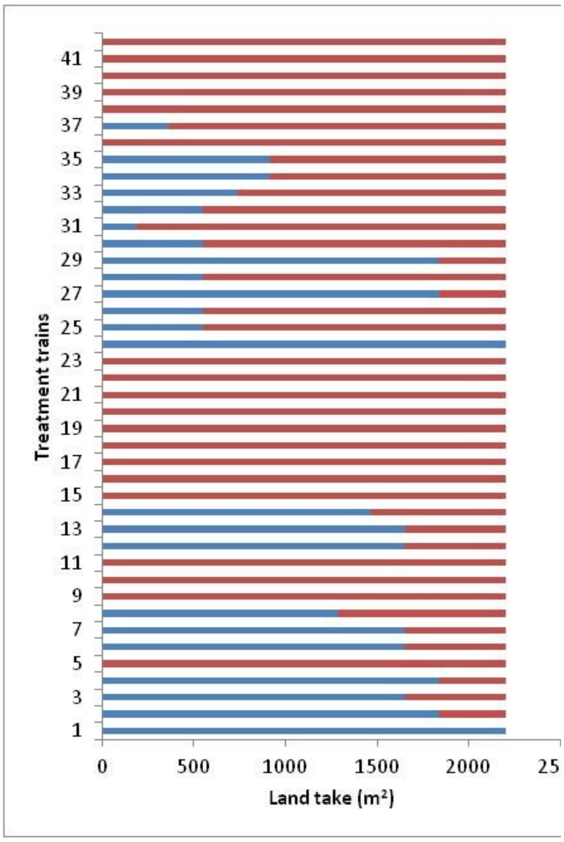


Figure 5-14: Achievable land take reduction (No attenuation)

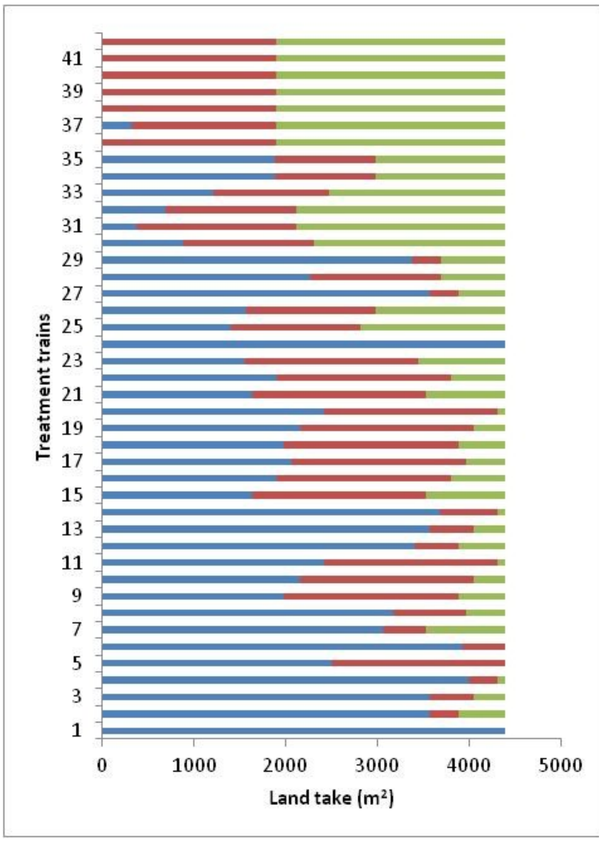


Figure 5-15: Achievable land take reduction (30 years return period)

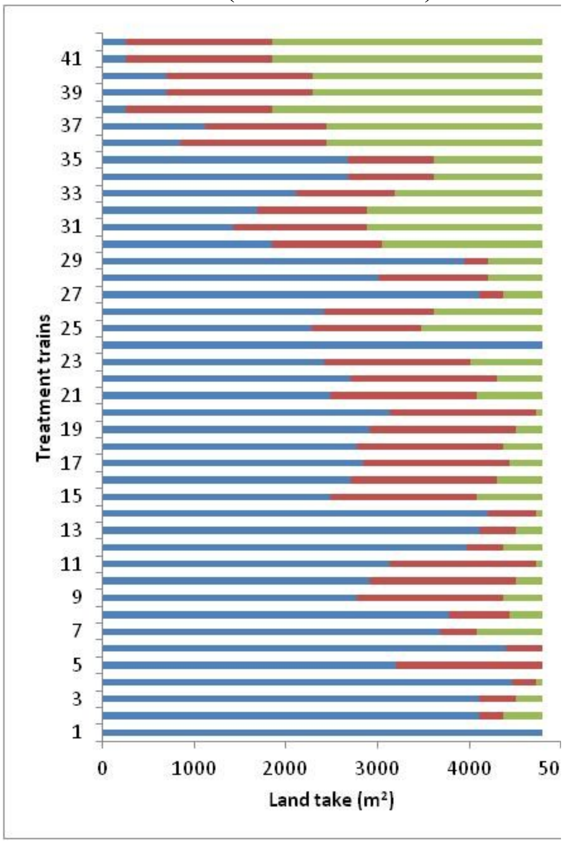


Figure 5-16: Achievable land take reduction (100 years return period)

1*	RP
2*	RP GR
3*	RP CBP
4*	RP WB
5*	RP LW
6*	RP SW
7*	RP CBP GR
8*	RP CBP WB
9*	RP LW GR
10*	RP LW CBP
11*	RP LW WB
12*	RP SW GR
13*	RP SW CBP
14*	RP SW WB
15*	RP LW GR CBP
16*	RP LW GR WB
17*	RP LW CBP WB
18*	RP SW LW GR
19*	RP SW LW CBP
20*	RP SW LW WB
21*	RP SW LW GR CBP
22*	RP SW LW GR WB
23*	RP SW LW GR CBP
24	RP
25	RP IT
26	RP SW
27	RP GR
28	RP CBP
29	RP SO
30	RP IT GR
31	RP IT CBP
32	RP IT SO
33	RP SW GR
34	RP SW CBP
35	RP SW SO
36	RP IT GR CBP
37	RP IT GR SO
38	RP SW IT GR
39	RP SW IT CBP
40	RP SW IT SO
41	RP SW IT GR CBP
42	RP SW IT GR SO

Regional control land take

Achievable land take reduction based on **water quality** benefits

Achievable land take reduction based on **water quantity** benefits

With:
CBP: Concrete block pavement
GR: Green roof
IT: Infiltration trenches
LW: Linear wetland
RP: Regional pond
SO: Soakaway
SW: Swales
WB: Water butts
* The techniques used for these treatment trains are designed to prevent infiltration

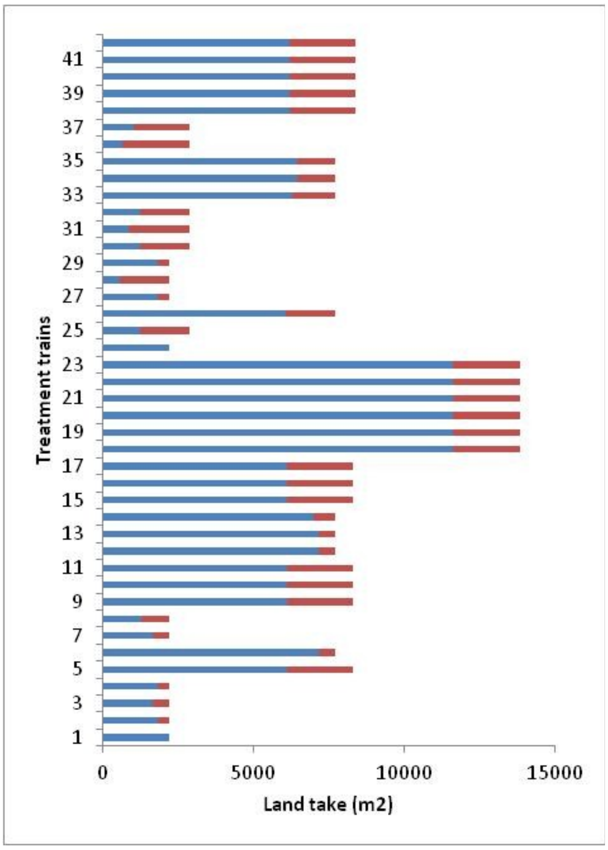


Figure 5-17: Achievable land take reduction for the treatment train (no attenuation)

1*	RP
2*	RP GR
3*	RP CBP
4*	RP WB
5*	RP LW
6*	RP SW
7*	RP CBP GR
8*	RP CBP WB
9*	RP LW GR
10*	RP LW CBP
11*	RP LW WB
12*	RP SW GR
13*	RP SW CBP
14*	RP SW WB
15*	RP LW GR CBP
16*	RP LW GR WB
17*	RP LW CBP WB
18*	RP SW LW GR
19*	RP SW LW CBP
20*	RP SW LW WB
21*	RP SW LW GR
22*	RP SW LW GR
23*	RP SW LW GR
24	RP
25	RP IT
26	RP SW
27	RP GR
28	RP CBP
29	RP SO
30	RP IT GR
31	RP IT CBP
32	RP IT SO
33	RP SW GR
34	RP SW CBP
35	RP SW SO
36	RP IT GR CBP
37	RP IT GR SO
38	RP SW IT GR
39	RP SW IT CBP
40	RP SW IT SO
41	RP SW IT GR CBP
42	RP SW IT GR SO

Regional control land take

Achievable land reduction based on water quality and quantity benefits of source and site controls

With:
CBP: Concrete block pavement
GR: Green roof
IT: Infiltration trenches
LW: Linear wetland
RP: Regional pond
SO: Soakaway
SW: Swales
WB: Water butts

* The techniques used for these treatment trains are designed to prevent infiltration

5.1.5 DISCUSSION

The methodology presented in Chapter 3 and applied to the Dalmarnock Road Area offers an opportunity for the key stakeholders involved in the drainage of surface runoff in urban areas to maximize the benefits of using SuDS in a treatment train. The assessment of the potential treatment trains for the area has underlined the following:

- The use of several SuDS in series affects the overall costs and land take, thus confirming stakeholders' fears. However, the extents to which costs and land take are affected vary depending on the techniques used with some techniques having a relatively low impact.
- A significant reduction in regional land take (up to 100%) can be achieved based on water quality and quantity benefits of source and site controls. This reduction should be seen in the context of increased costs and/or land take of the treatment train.
- Some techniques have clearly been identified as having a large land-take or cost impact while some others have a less marked impact.

- The potential reduction in land take associated with the regional control should be considered alongside an increase in costs or land take associated with the development of source and site controls.

5.2 HOUSTON INDUSTRIAL ESTATE

The Houston Industrial Estate case study was chosen from a wide range of available sites where the methodology could have been applied because its land use, site and catchment characteristics were significantly different from the previous case studies. This choice supports the underlying aim of providing a framework applicable to a wide range of situations where SuDS implementations are needed.

5.2.1 CASE STUDY

The Houston Industrial Estate, situated west of Livingston in Scotland, is a 220 ha area. The area is partly drained by a separate system discharging to an offsite regional control composed of a pond and a wetland in series (Figure 5-18 and Figure 5-19).

Figure 5-18: The Houston Industrial Estate and its regional control situation

Figure 5-19: The existing regional control at the Houston Industrial Area

The activities at the Houston Industrial Estate site comprise a wide range of industrial operations which generate traffic such as retail and business outlets, offices and equipment storage areas. In addition to the normal traffic load one would expect, a large number of plots are also dedicated to product manufacturing and this is reflected by a high number of chemical storage containers on the site.

Figure 5-20: Typical land uses for the Houston Industrial area and encompassing parking lots, busy roads, storage areas and on-site storage of chemicals

These industrial activities are the source of the diffuse pollution observed in the nearby Caw Burn which the surface water system drains to - including hydrocarbons, detergents, nutrients and suspended solids (Heal et al., 2005b). The site, originally designed to be drained by a traditional separate drainage system, was improved in 1996 when a pond and a wetland were implemented to tackle water quality issues reported in the downstream watercourse. The pond and the associated wetland were retrofitted as an end-of-pipe system – the design being compromised by the lack of space available (D'Arcy et al., 2007). Despite the significant improvements which have resulted from adding the pond and wetland, the Caw Burn passing from classification D to C downstream of the site, water quality is still considered as unsatisfactory within the context of the European Water Framework Directive (SEPA, 2006).

The work undertaken at the Houston Industrial Estate takes place in the context of a site which has been investigated for the purpose of improving water quality of the runoff discharged in the nearby Caw Burn. Two major studies have been produced on which the work undertaken for the presented research has been based. A summary of these two reports aiming at underlying the main findings is presented below.

Caw Burn Wetland and Catchment Improvements Project Stage 1: Final Report (Heal et al., 2005a) report the causes of poor water quality in the Caw Burn. The work undertaken at this stage has underlined the poor water quality entering a under designed regional control and resulting in intermittent discharges of polluted runoff. The report demonstrates the positive aspect of SuDS on water quality while the performances are judged not satisfying in regards to the expected water quality standards for the receiving watercourse in the context of the European legislation detailed in Section 2.1.1.3. The report also summarises wildlife observations and biodiversity assessment conducted by Pond Action (Pond Action, 2000): despite observers have been able to identify wildlife in close proximity to the wetland, the biodiversity of the system including fauna and flora, has been reported to be very poor by comparison with similar natural systems. The report investigates in detail the performance of the existing regional control composed of a pond with a capacity of $610m^3$ and a wetland in series with an estimated capacity of $3248m^3$. Although there is some flexibility in the design of the regional controls, these estimates are far below latest design recommendations for an industrial site (CIRIA, 2007; Scottish Water, 2007). The main findings highlight that estimated sediment accumulation in 2004 reduced the volume capacity of the pond by 25%. In addition, preferential pathways of water have been identified in the wetland and short circuiting of water flowing over the bank of the wetland has been observed during rainfall events. This impacts on the retention time of the runoff in the wetland and thus reduces the possibility for the pollutants to be removed. With the aim of improving the quality of water discharged to the Caw Burn, the report suggests improvements to the system. These improvements mainly focus on potential improvements that can be undertaken at the regional control level and include remedial actions to be taken to increase capacity and retention time of the wetland. While these changes should be encouraged, the benefits in terms of water quality are estimated to be limited unless major changes are undertaken such as the construction of a secondary offline regional control or the flooding of the entire valley. These last two solutions; despite still not satisfying CIRIA and Scottish-Water recommendations in terms of volume and retention time, have been estimated sufficient by the authors to improve the water quality classification of the downstream Caw Burn to at least a class B. While no cost estimates have been provided, these last two solutions have also been estimated to be the most expansive.

Retrofitting Sustainable Urban Water Solutions (SNIFFER, 2006). The report, based on the results of (Heal et al., 2005a) investigates SuDS retrofitting opportunities for the area. The investigation is based on the methodology presented by Swan (Swan, 2002). Based on site characteristics, the report assess the potential barriers for SuDS retrofitting for the area before investigating in detail the potential for some locations of the site to be retrofitted with SuDS. Large scale retrofitting for the site is investigated using a Multi Criteria Decision Methodology (MCDM) taking into account economic, environmental, social and technical criteria. The methodology used to perform the MCDM is a qualitative ranking of the different options, the highest ranking being considered as the best. The environmental criterion are based on the number of treatment stages, water treatment volume as presented in Section 2.3.3, provision of amenity and natural habitat and peak flow and volume reduction. Consequently, criticisms formulated against the use of water treatment volumes as a measure of water quality improvements and formulated in Section 3.1 apply in this case. The application of the MCDM favour the retrofitting of SuDS devices at a large scale on the site in comparisons with the other options considered and including the extension of the existing regional control and different SuDS retrofitting at a smaller scale.

The knowledge presented by these two reports on the site was complemented by a site visit in March 2010. The site visit has not put in light significant differences to the work previously undertaken by Swan apart from the fact that new buildings were built on the north west of the site. These buildings, limited in size in comparison with the existing development incorporate pervious pavements (Figure 5-21). While design details of the pervious pavement are not known, it is assumed that the impact of these buildings in terms of water quality degradation and volume discharged is limited due to their relatively low coverage and the presence of source controls.

Figure 5-21: Recent constructions in the North West part of the Houston Industrial site and including source controls

In response to the produced research and needs, the presented research investigates the potential to improve water quality standards by retrofitting site controls upstream of the existing SuDS system to improve water quality in the local water course. As the potential to implement SuDS in residential areas has been discussed in the previous section, the presented research focuses on the industrial area likely to be a greater source of pollutants due to the high potential pollutant loads (Duncan, 1999) and the risks presented by an accidental spill.

5.2.2 SELECTION OF POTENTIAL SUDS TECHNIQUES (PHASE 1)

As would be expected, the potential for SuDS retrofitting on the industrial site is largely influenced by the site characteristics. The high groundwater table at the site means the use of SuDS infiltration techniques has to be prevented as it may lead to contamination. Further to this, the existing land use and its infrastructure add an additional layer of complexity to the retrofit of SuDS devices. Although it is recognized that underground infrastructure such as cable or pipe networks could impede the implementation of some solutions, for the purposes of this study, only the visible infrastructure is taken as the limiting factor for the implementation of SuDS - this is similar to the approach used elsewhere (Todorovic et al., 2008b). Lastly, ownership of land and future development plans in the area could also be a significant barrier, especially when considering the land take associated with SuDS devices such as ponds. Within the context of these limitations, a detailed survey of the site undertaken in March 2009, in conjunction with the observation made by Swan (SNIFFER, 2006), has identified a limited number of SuDS that could potentially be retrofitted on the industrial site (Figure 5-22):

- A lined swale network where the road verges are large enough to drain road and highway runoff. Having the potential to drain only 10% of roads in the industrial area the retrofit of swales, despite draining highly polluted areas, are unlikely to have a major impact in terms of water quality (SNIFFER, 2006). Thus, swales will not be considered further despite their implementation being highly recommended in the treatment train philosophy (CIRIA, 2007).
- Where speed limits are likely to be below 60km.h^{-1}, impermeable parking area, loading areas and roads have the potential to be replaced with permeable surfaces. Inspection of site activities during a visit revealed that only a limited amount of surfaces are likely to be unsuitable for the implementation of pervious pavement due to localised industrial activity generating a large amount of fine particles which could clog the pervious pavement. Consequently, pervious pavements are considered as suitable for retrofitting in most of the industrial areas. It is assumed that pervious pavements will be designed to attenuate flows from events up to a 30 year return period.
- Within the site, space was found for 10 small ponds designed with a 0.6m depth permanent pool with an extended detention depth of 0.6m for attenuation. The surface area of the pond is dependent of the land available at each location (assuming pond land take will occupy a maximum of 70% of the land available at each of the 10 sites).
- In addition to the ponds and permeable surfaces, sub-surface storage can be envisaged anywhere on the development when additional attenuation storage is necessary.

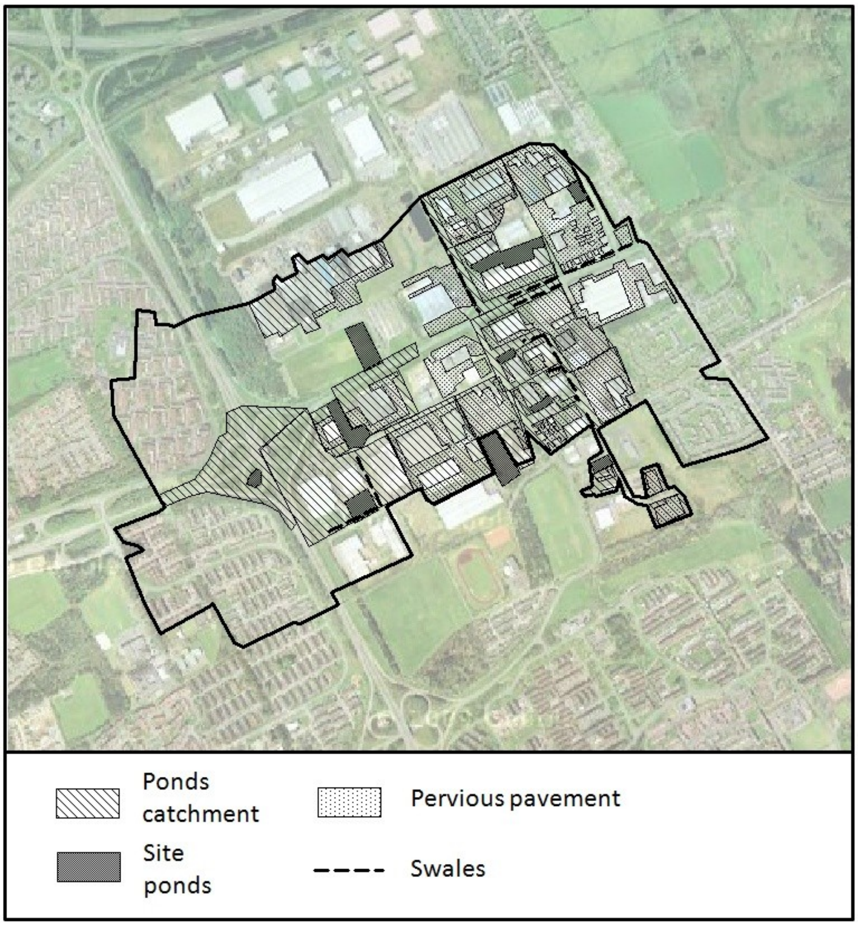


Figure 5-22: Potential SuDS deployment

The use of pervious pavement (source control) discharging into site ponds (site controls) which in turn are discharging into the regional control would constitute an ideal application of the treatment train philosophy (CIRIA, 2007). However, based on conclusions of the previous case study investigated, the use of two SuDS in series (Source-Regional or Site-Regional) is considered as sufficient to provide treatment to the runoff while a full treatment train (Source-Site-Regional) would be too restrictive in terms of needs of the stakeholders – cost and space. Consequently and in order to optimize the implementation of SuDS, the retrofitting of more than two SuDS in series has not been investigated.

Considering each SuDS that could be implemented to improve water quality and manage water quantity on site give a wide range of feasible treatment train solutions that could be implemented. The use of 1 to 10 different site ponds give over 1000 viable treatment train configurations that could be complemented by the use of pervious pavement and subsurface storage to reach water quality and quantity targets. The selection of the optimal solution should be undertaken based on the holistic assessment of these solutions ability to meet stakeholder needs while overcoming potential barriers.

5.2.3 ASSESSMENT (PHASE 2)

This section provides details on how the indicators selected in the previous section have been estimated.

Whole Life Costs

The retrofit of SuDS devices at the Houston Industrial Estate takes place in a specific context of an existing separate network and an existing separate pipe system. This case study, which is dominated by existing infrastructure, is significantly different from the previous case study where only the infrastructure would have to be developed. Considering the funding has been found for the construction and the maintenance of both the existing separate network and the existing regional control, the evaluation of the whole life cost only considers the construction and the maintenance of the retrofitted source and regional control for which additional funding would have to be found. This point of view is consistent with the idea that the construction of these new SuDS is the current barriers to the implementation of the treatment train.

The relatively low number of SuDS selected for the area and the relative amount of research which has been conducted on their whole life costs has lead to the application of the two methodologies presented in the Section 2.5.3. This has the advantage of determining whole life costs taking site specific details into account while putting the costs back in the wider context of the reported costs for different cases studies.

The methodology using the bill of quantities is based on recent guidance published in the UK for estimating SuDS capital and maintenance costs using bill of quantities method (UKWIR, 2005). The maintenance activities assume a high maintenance standard is undertaken. This assumption is based on the conclusion of the Chapter 4 which underlines the importance of high maintenance rate as an opportunity to satisfy more effectively residents living in close proximity. While the amenity provided by the ponds in the industrial areas has certainly less impact than the amenity provided by ponds in a residential area, it can be opposed the fact that:

there is a residential area in close proximity;

some businesses implemented on the site meant to attract customers, and;

the regional control is already used as a pet walking are for the residents as observed during the site visit.

Assumptions regarding the maintenance activities and their frequencies are summarized Table 5-4. The costs are determined by calculating construction and maintenance costs over 50 years and are then summated to provide a present day value using a 3.5% discount rate for the first 30 years and a 3% value for the remaining years (HM Treasury, 2003).

SuDS [reference]	Maintenance activities	Frequency (months)
Site ponds (UKWIR,2005)	Sediment removal from engineered silt trap	6
	Sediment removal from forebay	36
	Sediment removal from the pond	120
	Vegetation replacement	300
	Removal and disposal of construction sediments	once after 12 months
	Inspection, reporting and info management	1
	Litter and minor debris removal	1
	Grass cutting	4
	Barrier vegetation pruning	36
	Barrier vegetation weeding	12
	Aquatic vegetation management	12
	Algae removal	4
Sub-surface storage (Duffy et al., 2008)	Controlled disposal / Haulage of silt	120
	Remove blockages	120
	Jetting	120
	Repair broken components	120
	Grass cutting	1.5
	Litter removal	1.5
	Inspection of structures	6
	Desilt inlets & outlets	12
Concrete block pavement Scholz et al., 2007; UKWIR, 2005)	Remove block paves and stockpile to be washed	300
	Install replacement geotextile, install new 5mm single aggregate bedding layer and reinstate block.	300
	Inspection, reporting and info management	1
	Litter and minor debris removal	1.5
	Permeable pavement sweeping	4

Table 5-4: Maintenance regime for the different SuDS

The second methodology used to determine cost variability is based on the assumption that costs are functions of the project size. To manage uncertainty two scenarios have been investigated to determine the upper and lower costs limits for the SuDS considered. Thus, costs for the SuDS considered are based on the following assumptions:

- Capital costs for ponds are based on data collected by Brown and Schuler (1997) detailing the construction costs of 41 ponds. The maintenance regime assumes 3% to 6% of the construction costs are allocated to the yearly maintenance budget (USEPA, 2004).
- Capital costs for pervious pavement assume costs in the range £38.m^{-2} to £68.6.m^{-2} based on literature review reported by Taylor et al. (2005). The maintenance budget assumes pervious pavements cost up to £0.55.m^{-2} per annum (Taylor, 2005) but could decrease to near zero when there is no specific maintenance adopted other than sweeping that would be in use for other surface types.

Water quality and quantity

To comprehensively assess system performance, a hydrological and water quality model is developed using MUSIC 3.0. This section outlines the basis upon which the model was built using available data for the site to complement the theoretical background provided in Section 2.5.2.1.1.

The construction of the water quality model is largely based on the information provided by Swan (SNIFFER, 2006) who classified the different land uses into five types including residential, industrial roofs, highways, green areas and other industrial hard surfaces. Although values for some pollutant concentrations at the inlet of the SuDS regional control were available, this information came too late to be incorporated in the water quality model. In the absence of calibration values for TSS, TP and TN at the time the water quality model was developed, internationally reported values for the different surface types are used (Duncan, 1999) and it was assumed that analogous surface types identified on the site generate similar amounts of pollutants. A summary of the values used for the different surface types are illustrated Table 5-5.

	Residential	Industrial roofs	Other industrial hard surfaces	Highways	Green areas
TP ($mg.l^{-1}$)	0.40	0.13	0.32	0.26	0.072
TN ($mg.l^{-1}$)	2.60	1.82	2.60	2.10	0.83
TSS ($mg.l^{-1}$)	155	35	155	257	79
Area (Ha)	63.4	38.7	47.5	28.5	40.5

Table 5-5: Pollutants concentrations assumptions for the Houston area (based on (Duncan, 1999))

Table 5-6 summarises the main characteristics of the modelled runoff and the measurements of pollution concentrations at the inlet of the SuDS device before any treatment. Although the modelled values of the runoff are not equal to the measured values of the runoff, the values obtained are in the range of what would be expected for this type of catchment. Indeed, the modelled values are encompassed within the maximum and minimum values reported for the site to the exception of TP having an average modelled value below the minimum reported value but still very close.

	Measured			Modelled		
	TSS	TP	TN	TSS	TP	TN
Mean ($mg.l^{-1}$)	31	0.36	1.30	70	0.168	2.04
Maximum ($mg.l^{-1}$)	398	1.00	2.52			
Minimum ($mg.l^{-1}$)	3	0.20	0.5			

Table 5-6: Comparison of water quality modelled and reported values for the Houston Industrial area.

The modelling of pervious pavement, not included by default in the model, has been undertaken using internationally reported values on the monitoring of their performance. The varying performance reported in the literature serves as a baseline for two different scenarios (**Scenario 1 & Scenario 2**) which represent the upper and lower bounds of the performance data reported in the literature. The low performance scenario assumes pervious pavement achieve 50%, 49% and 33% for the removal of TSS, TP and TN respectively, while the high performances scenario assumes pervious pavement achieve 95%, 88% and 80% removal for TSS, TP and TN respectively (Gilbert and Clausen, 2006; Balades et al., 1992; Barrett, 2004; CIRIA, 2004).

The model is run with a time series rainfall of 146 months (from 01/08/97 to 30/09/2009) based on average values of reported rainfall for the area (MET Office, 2010).

Land take

Determination of the land occupied by the SuDS devices is undertaken using recent design guidance for the different SuDS devices (CIRIA, 2007; Scottish-Water, 2007). This includes any land required for access and landscaping.

5.2.4 RESULTS (PHASE 3)

5.2.4.1 Quantitative comparisons of SuDS source and site controls

The Figure 5-23 summarizes cost-pollutant removal relationship variability for the area considered. While the cost variability for any given removal rate is very broad for the SuDS considered, the comparison of their performance indicates that for the site considered, ponds are the best option for the removal of TSS at low cost, but the relative cost increase should be seen within the context of increased land take. Pervious pavement, not impacting on the land take, can achieve similar TSS removal but for a much higher cost. This result confirms why ponds are largely used as site and regional controls owing to their ability to achieve a relatively high removal at low cost.

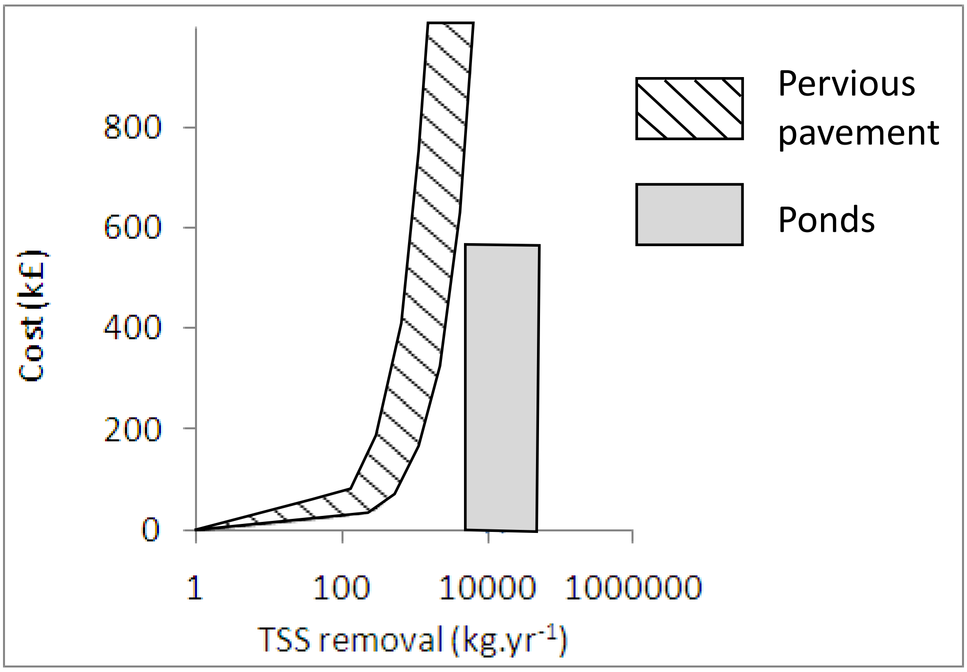


Figure 5-23: SuDS costs-pollutant removal relationship

While the reported cost variability for the SuDS considered is very broad, the variability associated with a treatment train would grow further as the number of devices considered also increases. The cost variability determined here would largely overlap for a significant number of treatment trains with, for example, the upper cost estimation for 2 ponds is comparable with that of the lower costs for 10 ponds. This aspect underlines the difficulty faced by decision makers in reaching a final decision within the context of fuzzy information available and underlines the necessity of estimating site specific costs.

5.2.4.2 Available solutions to complement water quality and quantity deficiencies

To face the wide variability of the costs reported in the previous section, site specific costs have to be determined. A further cost estimate, based on bills of quantities and taking into account site details and any additional costs associated with specific retrofitting issues (i.e. modification of pipe network, rerouting of underground pipes and cables) will have to be undertaken in the design phase - the objectives here being to provide only an estimate of likely costs.

In order to meet different water quality requirements, different scenarios based on the implementation of site ponds and pervious pavements complementing the existing SuDS system are considered. Individual results regarding pond performance are reported in Table 5-7. These results underline that pond performance for the removal of TSS were different from a site to another. Values for annual TSS removal ranged from 7.2 10^3 $kg.yr^{-1}$ to 33.8 10^3 $kg.yr^{-1}$. Pond performance is largely driven by the size of the permanent pool - the best performing ponds were also the largest in size. The hypothesis has been made that, if ponds were due to be retrofitted on the site, the decision regarding their implementation would focus on the best performing ponds.

SuDS	Catchement area drained (ha)	Average annual TSS removal (10^3kg)	Present value (k£)	Land take (m^2)
Pond 1	10.6	7.2	470	13000
Pond 2	4.5	12.2	394	9093
Pond 3	14.9	28.7	304	2966
Pond 4	1.2	33.8	371	6808
Pond 5	15.8	25.8	445	12075
Pond 6	12.9	23.1	437	11655
Pond 7	4.8	8.2	302	2899
Pond 8	7.3	15.5	275	1805
Pond 9	7.1	9.5	276	1821
Pond 10	3.4	8.2	285	2183

Table 5-7: Ponds performance

In order to reach the removal target, the retrofit of 0 to 10 ponds, was complemented by the retrofitting of pervious pavement. When attenuation is considered, the ability of the SuDS site controls to attenuate runoff is complemented by the use of sub-surface storage. Figure 5-24 to Figure 5-35 present potential attenuation with varying water quality performance levels for TSS, TP and TN and considering various attenuation requirements.

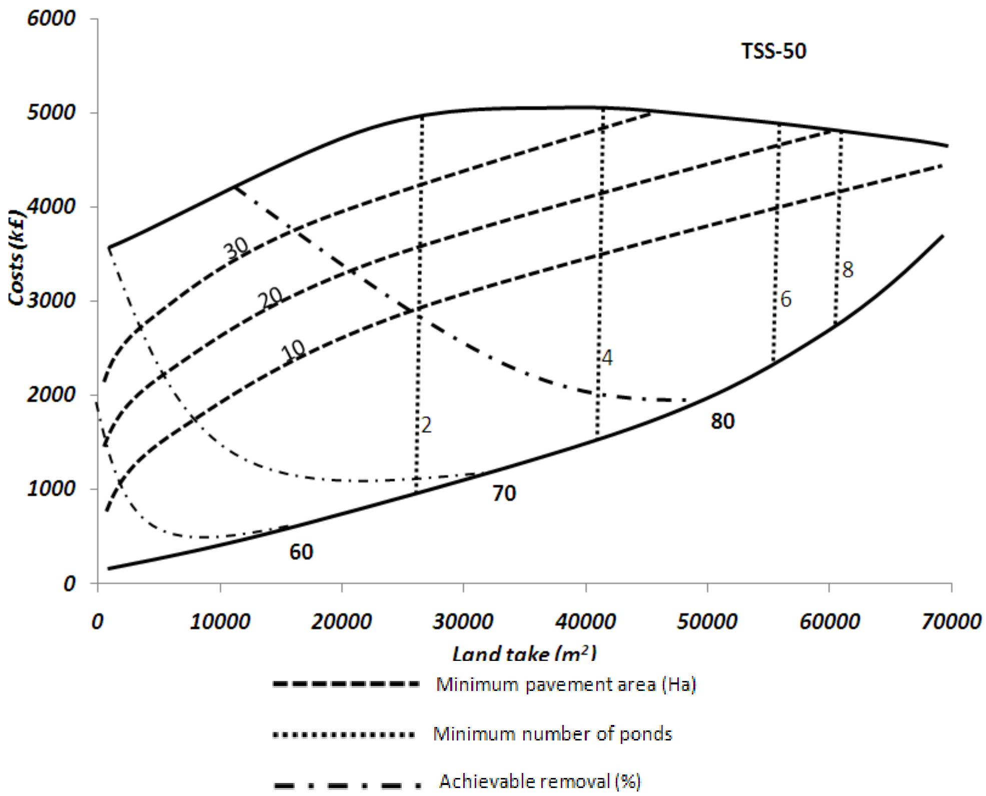


Figure 5-24: Expected TSS removal considering low SuDS performances without specific attenuation

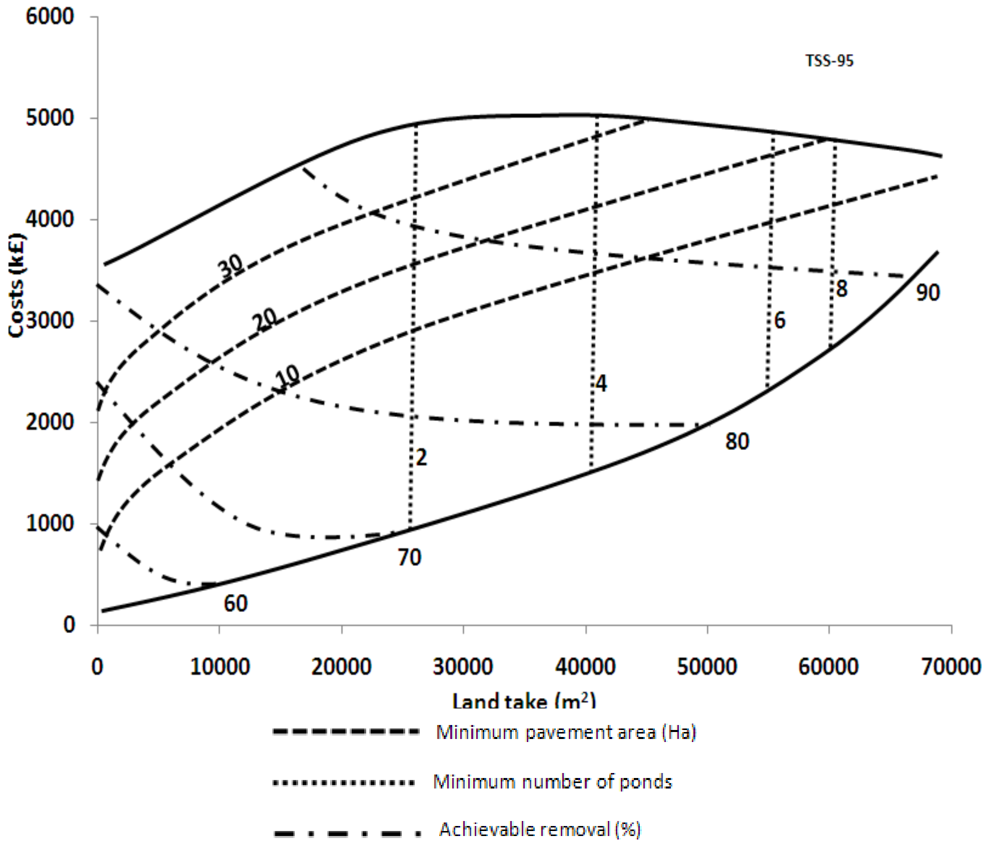


Figure 5-25: Expected TSS removal considering high SuDS performances without specific attenuation

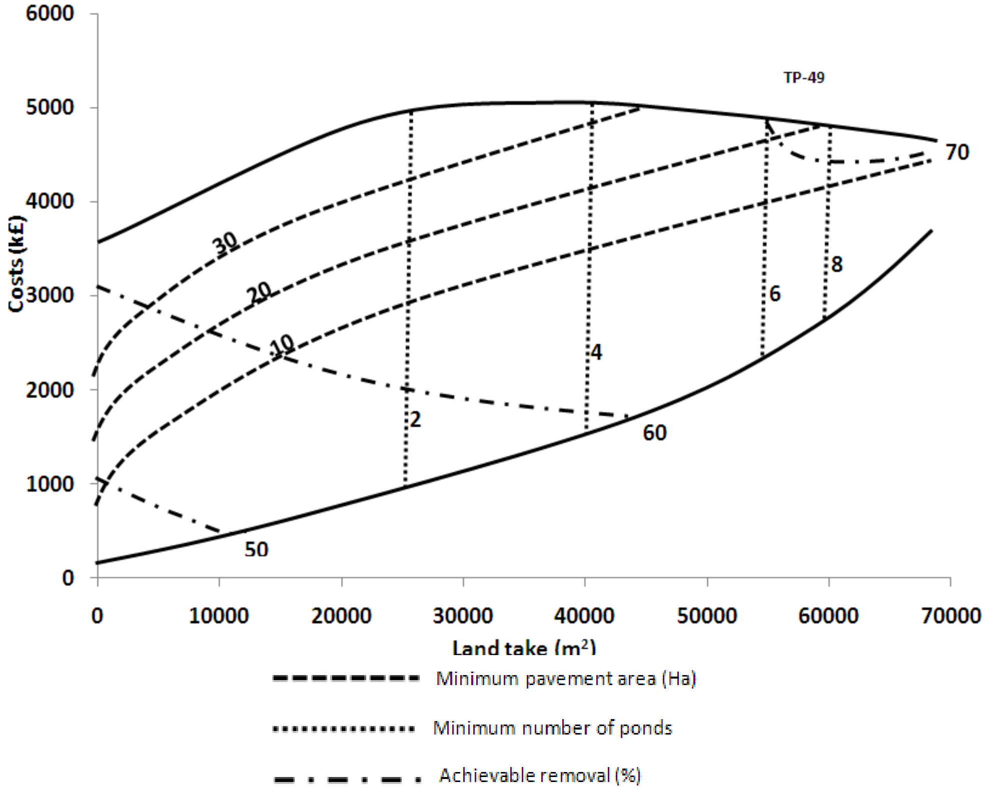


Figure 5-26: Expected TP removal considering low SuDS performances without specific attenuation

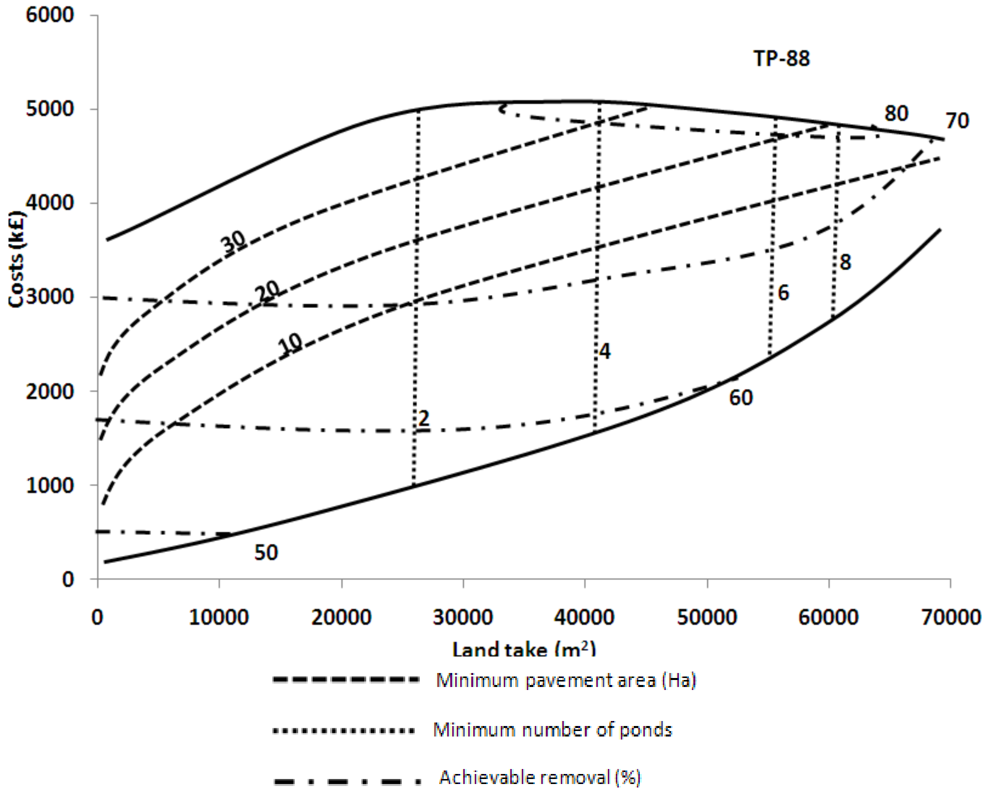


Figure 5-27: Expected TP removal considering high SuDS performances without specific attenuation

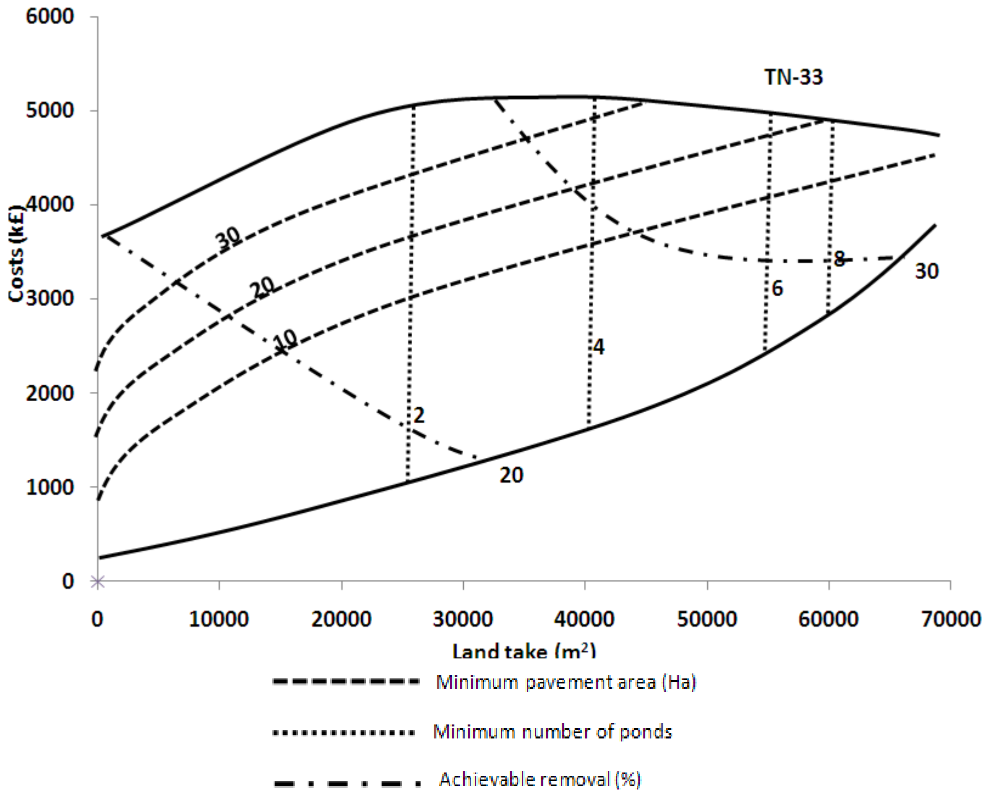


Figure 5-28: Expected TN removal considering low SuDS performances without specific attenuation

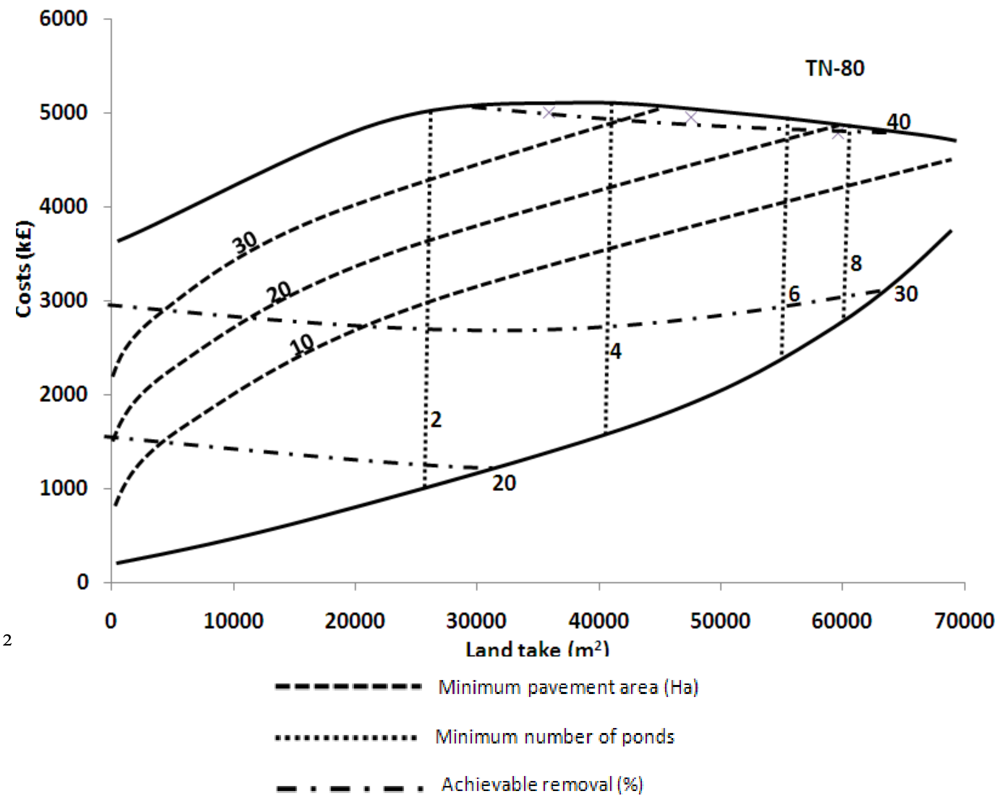


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Figure 5-29: Expected TN removal considering high SuDS performances without specific attenuation

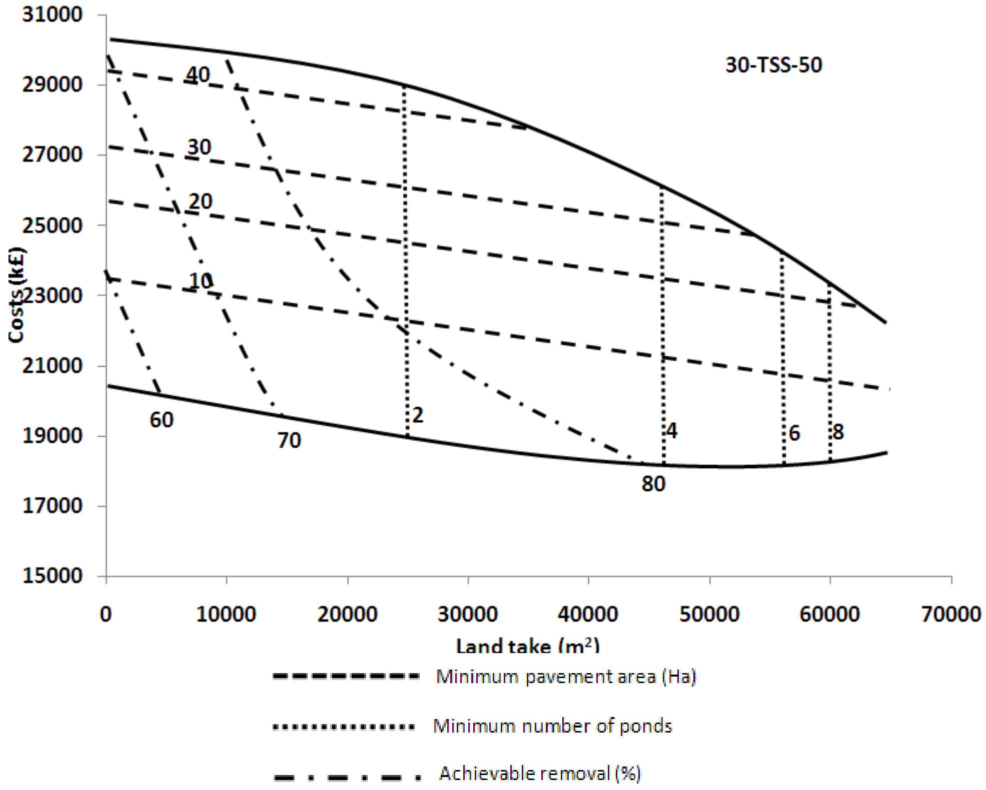

Figure 5-30: Expected TSS removal considering low SuDS performances for a 30 year return period attenuation

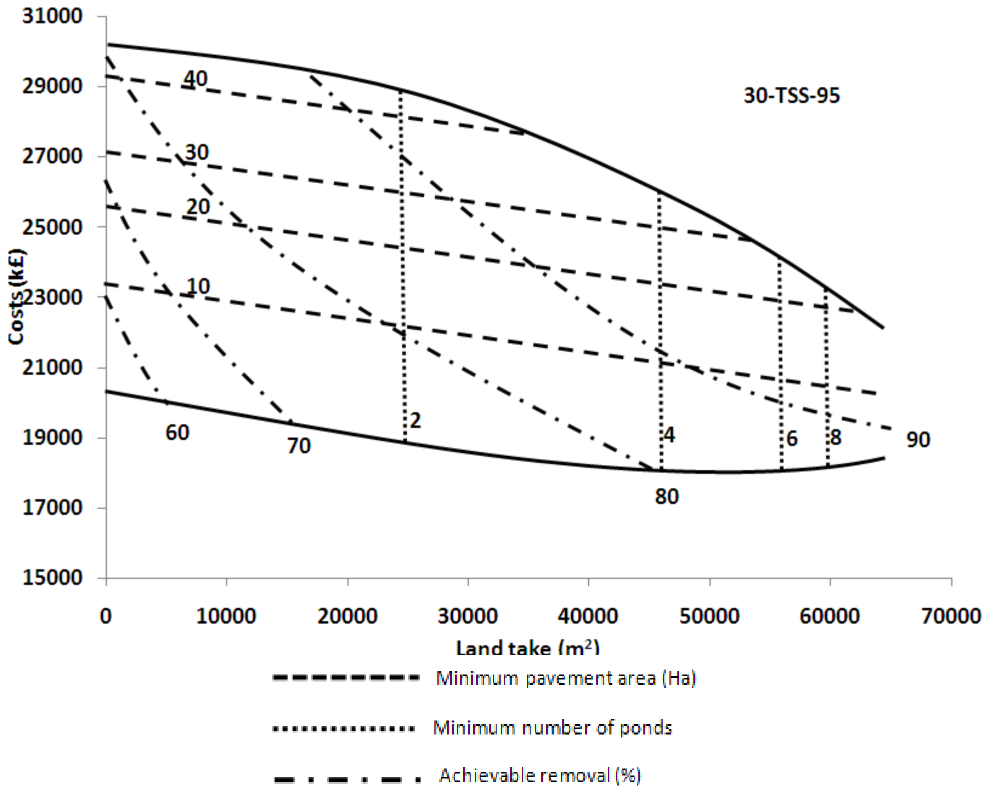

Figure 5-31: Expected TSS removal considering high SuDS performances for a 30 year return period attenuation

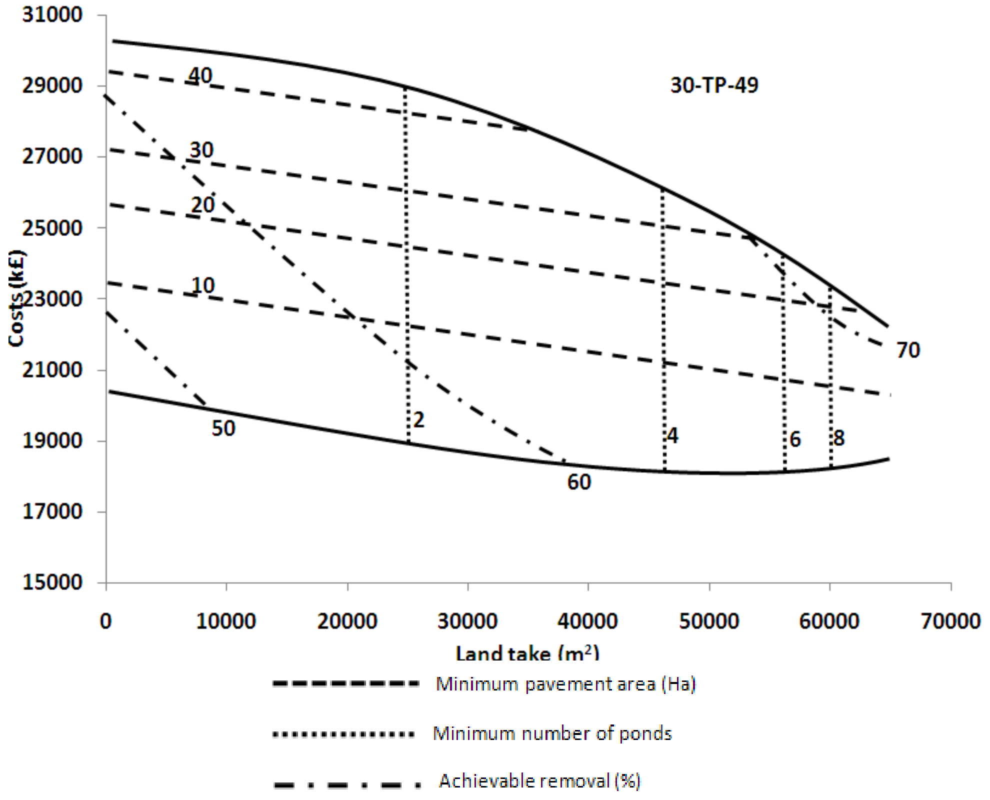

Figure 5-32: Expected TP removal considering low SuDS performances for a 30 year return period attenuation

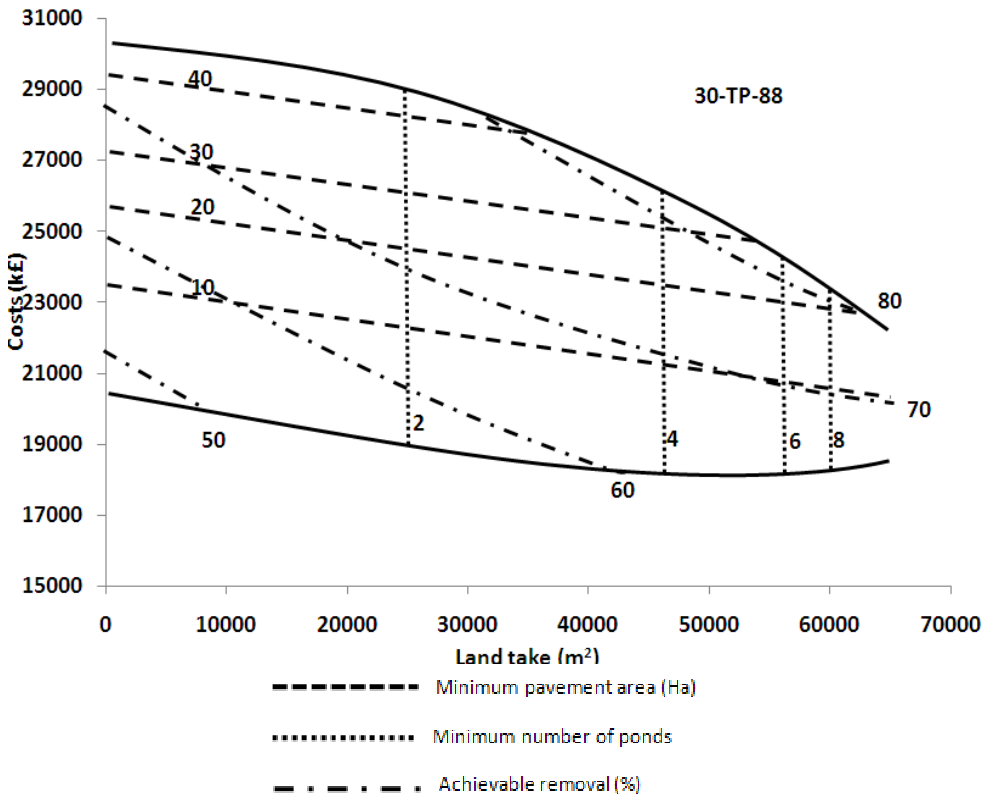

Figure 5-33: Expected TP removal considering high SuDS performances for a 30 year return period attenuation

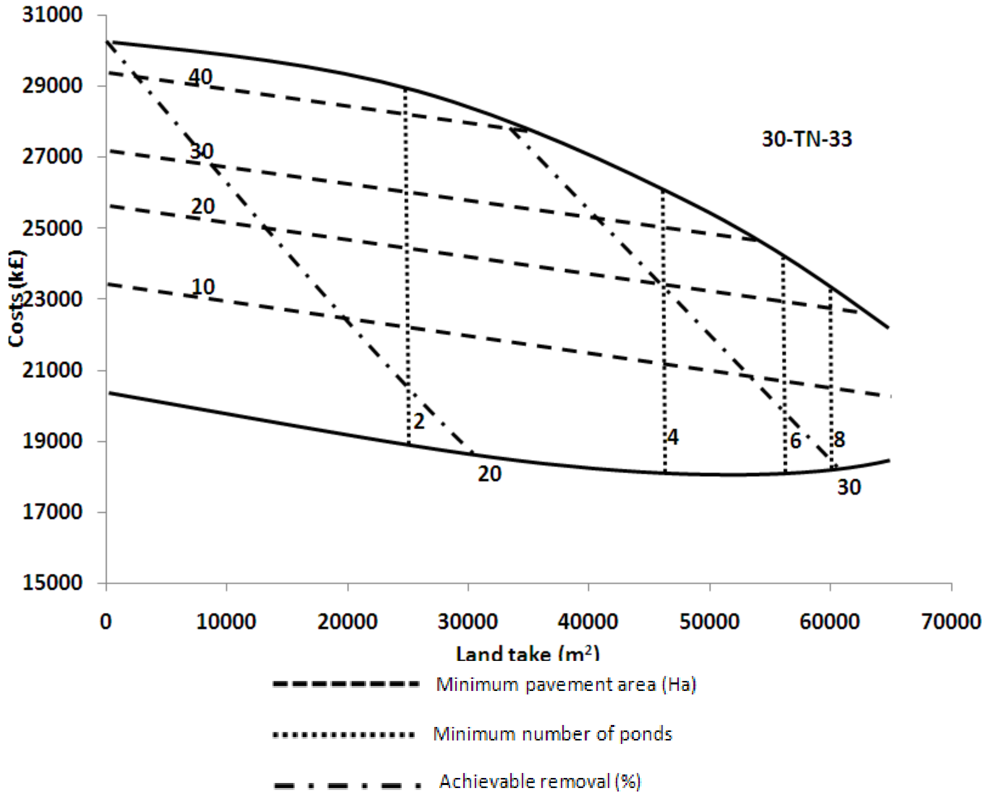

Figure 5-34: Expected TN removal considering low SuDS performances for a 30 year return period attenuation

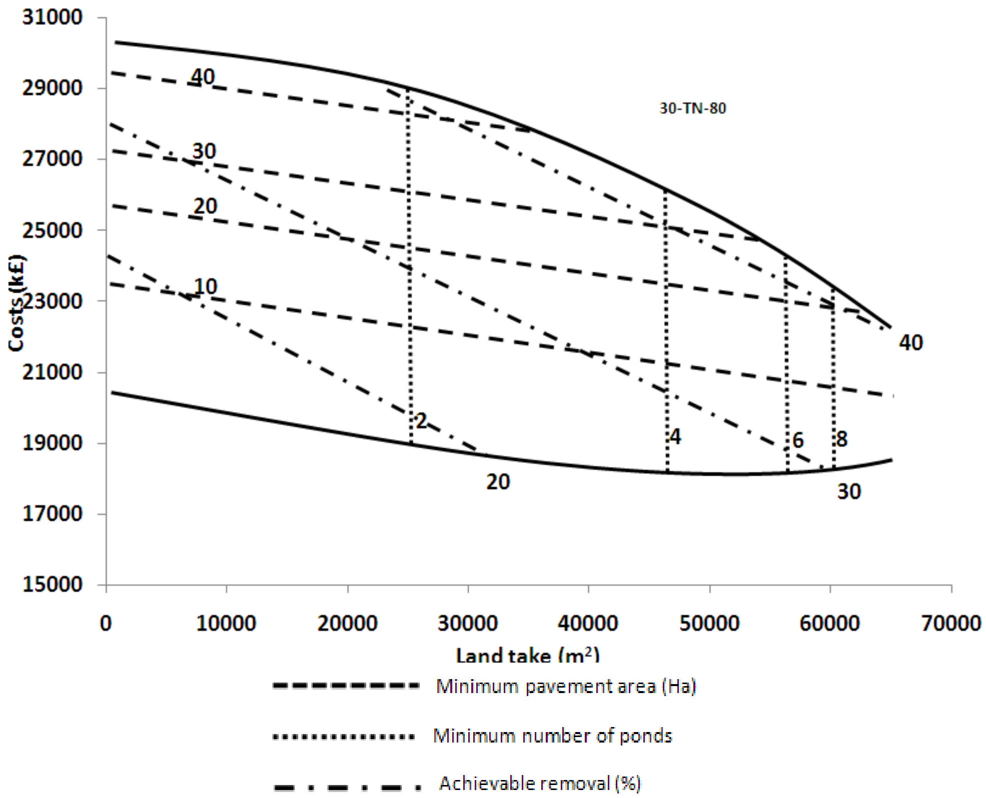

Figure 5-35: Expected TN removal considering high SuDS performances for a 30 year return period attenuation

The plots provide a visual presentation of relationship between the benchmarks for the stakeholder drivers and barriers defined in the methodology. They demonstrate that water quality improvements should be seen within the context of costs and/or land take increases for the pollutant considered. These increases are characterized by cost and land-take relationship for a removal objective. The increase in land take is driven by the use of site ponds, whereas the increase in costs is mainly driven primarily by the use of pervious pavement and, to a lesser extent, by ponds. For the attenuation of a 30 year return period storm, an additional minimum of £2.10^6 is needed to complement the attenuation provided by site ponds and pervious pavement using sub-surface storage.

The uncertainty associated with permeable pavement performance impacts on the overall removal efficiency. For example, if efficient removal of TSS is considered along with no attenuation the use of 4 ponds and the retrofit of 10 Ha of pervious pavement is sufficient to reach a 80 - 90% reduction in suspended solids. Conversely, if a low removal efficiency is assumed, the reduction is only of 70-80%.

As discussed previously, the current SuDS regional control is largely under-designed compared to the most generous design (Scottish-Water, 2007; CIRIA, 2007). Designing the regional SuDS system to the most generous design would mean the inclusion of a 2m deep permanent pool pond capturing the equivalent of 1Vt (58,100m^3) and a 0.6m deep wetland capturing the equivalent of 3Vt (232,400m^3). The surface area necessary to accommodate the theoretical SuDS regional control would be of 320,000 m^2 (against 5000m^2 for the current system). The attenuation of a 30 years return period would require the storage an additional 144 000m^3 either accommodated at the pond level adding an additional 15 000 m^2 or using sub-surface storage adding £19.10^6 to the cost of the project. The modelling of a theoretical SuDS regional control designed to the current requirement for SuDS using MUSIC achieves the theoretical removal of 94.4%, 71.3% and 55.7% for TSS, TP and TN respectively. Using these results as the design objectives for the retrofit scheme would necessitate the full implementation of the site solutions. According to the low efficiency scenario with no attenuation, a minimum of 8 ponds with 20 hectares of retrofitted pervious pavement would be necessary to achieve the requirements for TSS and TP. The removal objective for TN is not possible to achieve within the retrofit solutions considered. Therefore, if this type of analysis was undertaken, it is likely that the performance of the theoretical regional control will not be adopted by the environmental regulator as the impacts of such measure would constraint further development in the area and considerable funding would be needed. However, significant improvements can still be made within acceptable cost and land takes limits. The MCDA approach developed in Chapter 6 allows the stakeholders to determine the most acceptable compromise solution.

5.2.5 DISCUSSION

This third case study investigated the retrofit of SuDS in an existing industrial area and support the conclusions obtained for the first case study: the implementation of SuDS should be seen within increases of costs and land take in most of the cases. Additionally, in this case the numbers of SuDS which potentially could be retrofitted are limited due to the existing infrastructure adding a level of complexity to the implementation of SuDS. In particular, the use of green roofs, presented as particularly interesting in the first two cases studies has proven to be impossible here because the existing infrastructure could not support it. This consideration put further in light the need for SuDS to be considered as early as possible in the development so as to maximise opportunities for SuDS implementation.

Despite the significant number of SuDS options that could potentially be implemented, the retrofit of source and site controls are not likely to compensate for poor water quality performance of the regional control. While significant improvements are achievable, the compensation of the regional control poor performance using only SuDS source and site controls impact on land and economical resources in a manner which is unlikely to be acceptable for the land owner. However, significant improvements, both in terms of water quality and quantity can still be achieved within reasonable costs and land-take footprint. In these conditions, the level to which SuDS retrofitting needs to be implemented may be decided as a function of the likely necessity for water quality improvements and attenuation of the runoff in the context of costs and land take impacts.

5.3 CONCLUSIONS AND IMPLICATIONS FOR FURTHER RESEARCH

This section has applied the methodology presented in Chapter 3 to three case studies. The case studies investigated offer different land uses, catchment and site characteristics. These different characteristics have largely impacted, first of all, on the choice of the SuDS that could potentially be implemented and secondly on the quantitative drivers for and barriers to the implementation of SuDS devices established in Section 3.3.2. Although direct comparisons of the water quality indicators are not possible, the investigations presented in the three case studies have underlined that:

the improvement in treatment efficiency and water quantity should be seen within the context of an increase in the costs and land take for nearly all the situations considered; and,.

increases in costs and land take are different for each case study considered.

Costs are largely influenced by the site characteristics, but also by the catchment specific water quality and quantity needs. Although the impact of using source and site controls can be seen as an opportunity to optimise SuDS footprint, the increases in costs and/or land take associated with the use of source and site controls are significant. Consequently, the increase in costs and land take are likely to be seen negatively unless land at the regional control is valued very highly. Moreover, the operation and maintenance of most of the source and site controls investigated would remain the responsibility of the land owner, either public or private (unless vested by Scottish Water). Thus, the construction, the adoption, the maintenance of most the SuDS investigated in the feasibility studies would remain the responsibility of developers, land owners or local authorities who would have to accept their extra costing and land take.

In conclusion, the research hypothesis is not verified and changes in water quality approaches and adoptions schemes will not be sufficient to encourage a wider uptake of SuDS devices. This is despite the evidence that SuDS can bring added benefits to the area where they are implemented.

Consequently, the implementation of SuDS in a treatment train, despite the numerous advantages presented in Section 2.2.2 are not likely to take place unless it is specifically required as a planning condition or significant incentives are put into place to encourage developers and land owners to implement and maintain them. A review of projects where a treatment train has been used shows that the use of source and site controls was strongly encouraged as a planning condition. In particular, for the two key Scottish projects presented in Section 2.2.4, the use of treatment trains was made a planning condition by the local authorities. Similarly, the use of source and site controls is now strongly encouraged as a part of a strategy to limit environmental impact of developed buildings (CEEQUAL, 2010). In addition, to improve their corporate image, companies may wish demonstrate a higher commitment to the sustainability agenda to help projects to pass through planning process.

As well as using the planning process, there may be other opportunities to support the implementation of treatment trains. In particular, changes to the current charging scheme for water utilities may encourage the use of source and site controls on private land. Indeed, the current charging scheme adopted by Scottish Water for water services includes drainage of rainwater based on the rateable value of the business and does not take into account the volume of water discharged (HMSO, 2002). This situation has been identified as a further barrier to the adoption of SuDS by private land-owners (Atkins, 2004; SNIFFER, 2006). As a result, the inclusion of source and site control within private land will not achieve a reduction of the charges unless complete disconnection is achieved. While complete disconnection is difficult to consider, the implementation of SuDS controls can achieve significant benefits. Thus, the attenuation of a 30 year return period event within a site has been investigated by Swan (SNIFFER, 2006) for the Houston Industrial Area. The result of the calculation for different scenarios demonstrates that the payback period considering the attenuation of a 30 year return period would be between 4 and 34 years depending on the site and the SuDS considered. Whilst the interest of the owner in investing beyond 20 years is debatable, the shorter payback period is indubitably interesting.

Chapter 6 - FRAMEWORK

This chapter, based on key findings from the previous chapter, details the development of a novel approach to help decision makers to optimise the implementation of SuDS treatment trains in different developments. The aim of the framework is to facilitate the production of SuDS designs which treat and attenuate runoff while optimising land take and whole life costs. This approach is entirely consistent with objectives set internationally to implement sustainable water solutions whilst having a limited socio-economic impact (e.g. Queensland Legislation (2009); US Senate (2009), European Communities (2000)). This Chapter will first present and justify the framework, and then apply it to the case studies presented in Chapter 5.

6.1 FRAMEWORK DEVELOPMENT

6.1.1 BACKGROUND FOR THE DEVELOPMENT OF THE FRAMEWORK

The literature review presented in Chapter 2 identified the benefits of using treatment trains. To better understand this, Chapter 3 proposed a methodology to benchmark some of the key benefits associated with their use. The methodology focused in particular on long term water quality and flood risk management benefits due to the certainty with which they can be modelled with current tools and thus be integrated early in the decision making process. Considering these benchmarks only, the development of treatment trains is not justified as the development of regional controls achieve similar benefits with lower land take and costs. This aspect was developed in Chapter 5, where it was shown that the implementation of treatment trains significantly increases costs and land take of the project (with the exception of green roofs used as part of a greenfield development). However, the benefits taken into account in the evaluation of the treatment trains in Chapter 3 and applied in Chapter 5 should be seen in the context of other benefits associated with the use of treatment trains. Although these benefits are important, associate a value with them at the design stage is a key challenge. They include:

- an improved degradation of the pollutants;
- a better management of the risks associated with an accidental spill;
- a better management of the risks associated with any eventual failure of the system;
- an extended SuDS lifecycle; and,

- an improved protection of the regional control.
- The last point is key. The potential benefits achieved in terms of water quality reaching the regional control through the use of SuDS devices upstream can be used to maximize the potential wildlife/biodiversity at the regional control and optimise return on investment for developers. These improvements should be seen within the context of other measures which impact significantly on public perception such as safety and design (Chapter 4).

Due to the relatively limited uptake of SuDS treatment trains, most of these benefits have hardly been described as a result of onsite monitoring. In these conditions, net benefits can only be determined with a high degree of uncertainty. However, they are key to the optimisation of urban drainage systems and can reasonably be expected in the context of the research presented in Section 2.2.2. Within this context, the framework developed in this chapter assumes that the implementation of source and site controls to complement regional control will contribute to the points developed above and result in a net benefit.

6.1.2 PRESENTATION AND JUSTIFICATION OF THE FRAMEWORK

The objective of the framework is to help decision makers, especially the environmental regulator and local authorities, to make a decision regarding the extent to which treatment trains should be implemented. This decision should be made by taking into account the benefits associated with the use of treatment trains but within the constraint of acceptable land take and costs to landowners and developers.

The proposed approach is to firstly meet water quality requirements in relation to the proposed environmental standards and secondly address quantity issues by satisfying attenuation objectives. The decision to separate water quality and quantity performance in this way is based on the observations that;

1) for high return period events, dedicated SuDS structures to attenuate runoff may be necessary (e.g. subsurface storage, dedicated attenuation at the regional control); and,

2) the use of SuDS structures can be compared to other strategies to manage water quantity (e.g. embankments).

Using the proposed water quality and quantity standards, benefits are benchmarked against socio-economic indicators which reflect land take, whole life costs of the SuDS techniques and allow the selection of the best treatment train. An overview of the different stages leading to the best treatment train is given in Figure 6-1 and described in the remainder of this section.

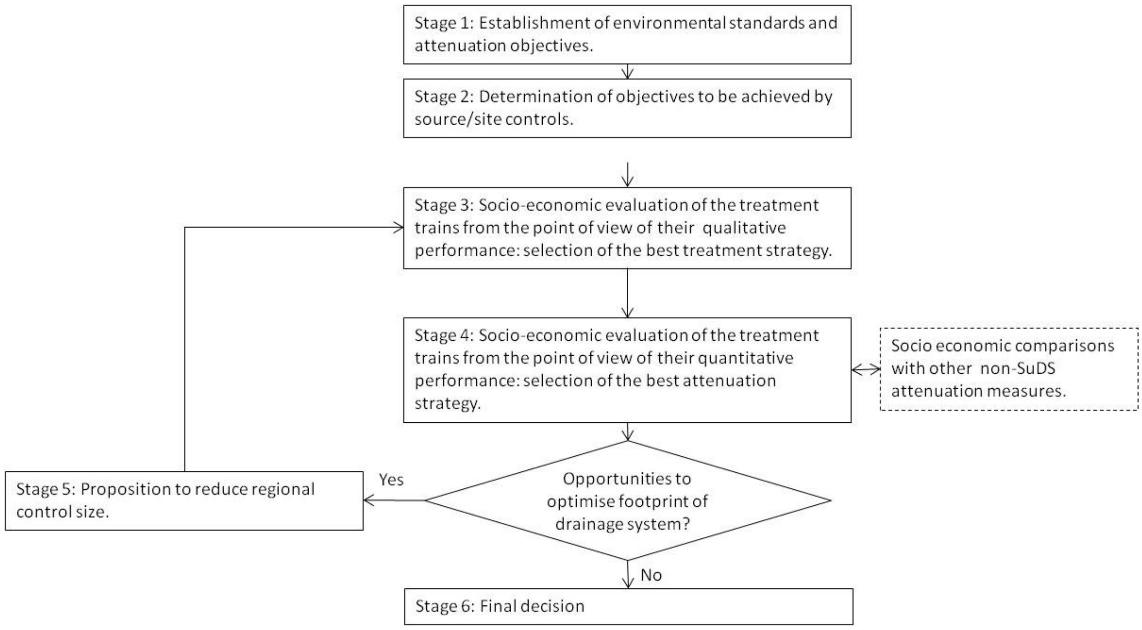

Figure 6-1: Framework flowchart

Stage 1: Establishment of environmental standards and attenuation objectives.

The current water quality design (Section 2.1.1) does not allow all SuDS type to be taken into account despite significant water quality benefits can be achieved. Moreover, the current “Vt” approach remain nebulous in its definition and has been criticised for it inconsistency (D’Arcy and Mclean, 2009). In response to this situation, a move from current simplified water quality design is proposed. The proposed approach favours SuDS modelling instead of SuDS design, and allows a wide range of SuDS to be assessed. This comprises modelling water quality indicators for the area based on local measurements or generic surveys which relate land use to pollutant generation associated with rainfall events (e.g. (Duncan, 1999; USEPA, 1983)). This analysis may then be used to establish theoretical long term pollutant concentrations to the receiving water body. Potential impacts of pollutants are benchmarked against environmental standards supporting good or high ecological status relative to the sensitivity of the receiving water body (Table 2-1).

Similarly, the impact of high flows for different return periods is established and allows an informed decision to be made by the environmental regulator and local authorities regarding the return period to be attenuated. This decision is supported by existing guidance on the subject (Section 2.3.4).

Stage 2: Determination of objectives to be achieved by source/site control.

A key action on the stakeholders is deciding to what extent the regional control and source/site SuDS contribute to the achievement of the environmental standards set in Stage 1. As underlined in Chapter 5, the removal of pollutants can be achieved at lower cost and land-take by specifying only a regional control (in comparison with costs and land take associated with source and site controls). Hence, the decision on to what extent source and site controls should contribute to the achievement of the environmental standards will impact directly on the costs and land take of the project.

The decision on to what extent regional controls and source/site controls contribute to meeting environmental standards should be seen within the context of the un-quantifiable benefits associated with the development of a treatment train (Section 2.2.2). The level, to which the regional control and source/site controls should contribute to achieving environmental standards can, in first instance, be decided by referring to:

- existing recommendations on the design of regional controls (Scottish-Water, 2007; CIRIA, 2007);
- existing recommendation on SuDS treatment train implementation (SEPA, 2006); or,
- where the regional structure already exists, the design and performance of the asset.

In the second instance, the initial design of the regional control, when based on existing recommendations, can be reviewed. Based on the water quality benefits associated with the use of source and site controls, less emphasis can be placed on the performance of the regional control. This option is investigated within stage 5 of the framework.

Stage 3: Determination of the socio-economic impacts and selection of the best treatment strategy.

The impacts of the different treatment train solutions need to be assessed from the point of view of their whole life costs and land take. The underlying hypothesis is that costs and land take associated with the development of SuDS are considered differently depending on:

- the geographical location of catchment investigated; and,

- the location of the SuDS assets within the urban fabric.

Indeed, land value can often vary considerably at national, regional and even development scales. However, whilst the space consumed by a regional control may be a valid concern of a developer, there may be less concern associated with source control devices. For example, the development of small SuDS within private curtilage or along the roads may be considered as having a lower impact on future development than the development of large facilities on developable land. However, the later type of implementation means these source controls have to be adopted by private owner, road or local authorities. In this case, maintenance costs are met by the adopter. Without regulatory requirements, source controls are not likely to be adopted unless subsidized by water authorities to cover land take losses, construction and maintenance costs of source controls. Within this context, cost and land take of the treatment train can be met by water authorities.

Based on these considerations, the framework proposes to aggregate whole life costs and the land taken by SuDS devices in “equivalent cost” (EC) according to Equation (6-1). Equivalent costs are calculated based on the sum of the whole life costs of SuDS and the potential return on the land taken.

$$EC = WLC_P + PRLT_P \qquad (6\text{-}1)$$

With:
WLC: Whole life costs (k£) of the SuDS project over a period P
PRLT: Potential Return on Land Taken over a period P

The objectives of the equation are here to determine the balance between the costs associated with SuDS construction and maintenance with the potential benefits that could be associated with the land taken.

The whole life cost of the SuDS project over the period can be calculated according to the definition provided in Section 2.5.3.

The potential return on land taken presents a more difficult value to determine. A methodology commonly used by developers to determine if investments are viable is to determine the potential return on investment of a project by determining the potential land rental value of an area. The Land Rental Value is determined based on the estimate of the Market Value (MV) of the land and the Capitalisation Rate (CR):

$$LRV = MV \times CR \qquad (6\text{-}2)$$

LRV: Land Rental Value (k£.Ha^{-1}.yr^{-1})
MV: Market Value (k£.ha^{-1})
CR: Capitalisation Rate (%)
The capitalisation rate (CR) being the net ratio between the net operating income produced by the land and its market value. The point of view of local authorities or land developers is here crucial to estimate the potential benefits on the long term of the future development.

The LRV is capitalised over the period of the useful lifetime of the asset to determine the Potential Return on Land Taken (PRLT). In the line with the methodology presented previously to determine net present value (NPV) for SuDS (Section 2.5.3) and potential value associated with amenity offered by ponds (Section 4.3), PRLT is determined over a period of 50 years at a discount rate of 3.5 % over the first 30 years and 3 % over the remaining 20 years (UKWIR, 2005; HM Treasury, 2003). A coefficient α is introduced to reflect the position and the impact of the SuDS within the urban fabric on further development:

$$PRLT_P = \alpha \times NPV_P(LRV) \qquad (6\text{-}3)$$

With α encompassed between 0 and 1. The values of α represent the relative importance of land taken by SuDS compared to their costs. The point of view of the land developer or the local authority is essential. As the value of α may vary from site-to-site, clear rules should be edited for setting it.
A framework for setting α can be defined as follows:

- α=0 when the land used for SuDS is not felt as an issue by developers and local authorities. This might be the case where land consumption is not limited or SuDS are implemented on land which cannot be further developed. This is the case for example where SuDS are part of the infrastructure (e.g. pervious pavement, green roofs) or have dedicated structures planned in the development plan (e.g. implementation of ponds within a park);

- α=1 in the case the potential land taken by SuDS devices could otherwise be used for development. This is the case for example where SuDS implementation takes place on land that could otherwise be used for construction;
- α is set between 0 and 1 for a range of solutions where the land is a valuable asset for developers and local authorities but cannot otherwise be used for construction. This might be the case with the development of swales or trenches along the roads: their development might not impact further development considering available land but will reduce the saleable land for local authorities and developers and thus reduce net benefit.

The equivalent costs may then be plotted against the modelled performance of each alternative treatment train (Figure 6-2). The graph obtained allows the identification of the group of dominant and dominated solutions. The dominant solutions are identified over dominated solutions as those having lower equivalent costs for equivalent or higher water quality performance and form a Pareto front. The dominant solutions thus reflect the preferences of stakeholders have vested in costs and land take. Benchmarked against environmental standards determined at Stage 1, the graph allows identification of the best treatment train 1) satisfying environmental standards and; 2) having the lowest cost/land take impact. The optimal solution is graphically selected amongst the dominant solution as the one satisfying environmental standards with the lowest equivalent costs.

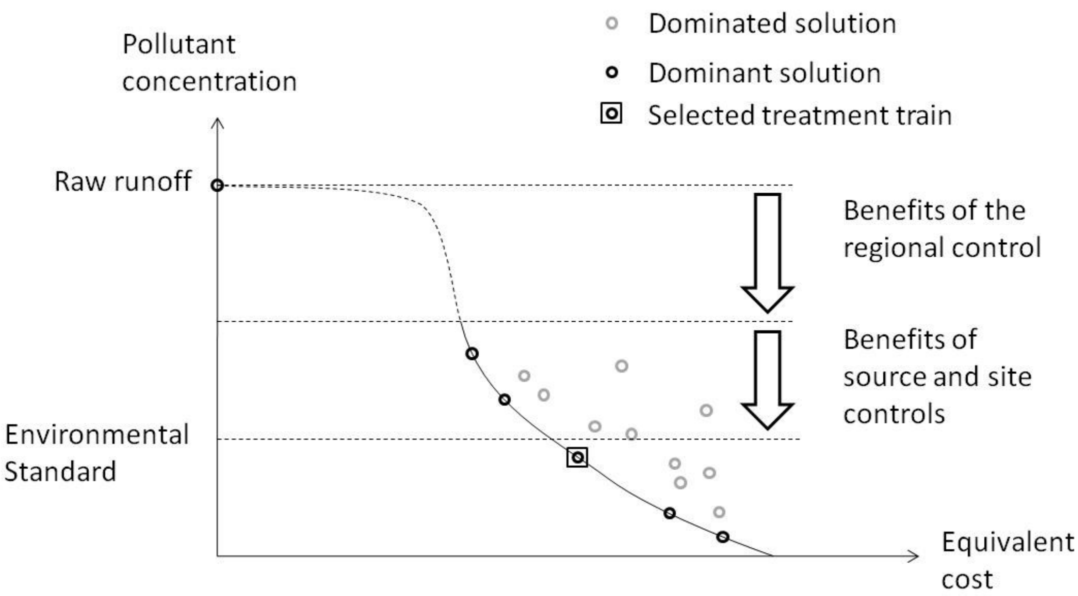

Figure 6-2: Identification of socio economic dominant solutions satisfying environmental standards.

Stage 4: Determination of the socio-economic impacts and selection of the best attenuation strategy.

While treatment is provided for small and frequent events mobilising most of the pollutants and responsible for the degradation of receiving water bodies (Section 2.1.1.2), SuDS also provide attenuation by allowing infiltration and/or temporary storage of runoff. However, attenuation of large return period events necessitates dedicated structures for the retention and/or infiltration of large volumes. These dedicated SuDS structures can impact drastically on land take and costs (Chapter 5). In these conditions, there is a need to evaluate cost and land take impacts of alternative solutions to attenuate the design return period. Calculation of the equivalent costs using Equation (6-1) supports the selection of the best approach for the selected return period. This approach also allows comparisons with non-SuDS solutions (section 2.3.4) to be undertaken.

Stage 5: Proposition to reduce regional control size.

Where possible, a reduction in the size of the regional control should be considered. This reduction is based on expected water quality benefits provided by upstream source and site controls. These benefits can be assessed by modelling SuDS performance through a water quality model. For treatment trains providing a treatment in excess of the required water quality standards, the regional control can be reduced until the most stringent parameter is equal to the minimum environmental standard. However, care should be taken as, as discussed in Section 5.1, the regional SuDS are the last control before runoff is discharged to the natural environment. Consequently, it is important to fully understand any uncertainty involved in assessing water quality performance. Considering the treatment trains with a reduced regional control, a loop from the Stage 3 of the framework is applied and the equivalent costs are re-calculated. The equivalent costs of the new solution can be compared with the initial equivalent costs to determine if the reduction of the regional control is justified or not.

Stage 6: Final decision

The application of the successive steps proposed in the framework allows:

- Identification of the best treatment strategy considering the costs and land take associated with the SuDS techniques;
- Identification of the best attenuation strategy by considering the costs and land take of the SuDS techniques;

- The basis for considering reducing the regional control based on water quality benefits of source and site controls.

6.2 APPLICATION OF THE FRAMEWORK

The framework provides a novel approach to optimise benefits to stakeholders'. This approach differs significantly from current practice which is largely constrained by legislation and the requirements environmental regulators. By taking into account SuDS performance instead of focusing on end-of-pipe controls, the presented framework is an approach that could potentially be used to satisfy environmental and flood protection requirements. To test the robustness of the presented approach, the framework is applied to the case studies presented Chapter 5: the Houston Industrial Estate and the Dalmarnock Road Area with the objective of selecting of the best treatment train which satisfies the environmental objectives whilst limiting land-take and costs impacts.

6.2.1 APPLICATION TO HOUSTON INDUSTRIAL ESTATE CASE STUDY.

As outlined in Section 5.2.1, the Houston Industrial Estate presently discharges runoff to an under-designed regional control system. As a result of the regional control being under-designed in terms of water quality, the discharge to the receiving water course (the Caw Burn) has resulted in significant pollution of the receiving water body. This situation is not compatible with the WFD objective of reaching good ecological status for the receiving water body. While a modification to the design of the regional control is considered as the cheapest solution (Heal et al., 2005a), this is not consistent with the treatment train philosophy and its associated benefits.

Investigation of the site presented in Chapter 5 demonstrated that the retrofit of ponds and pervious pavement can bring benefits in terms of water quality improvement and attenuation. However, land-take and costs impacts can also be significant. In this section, the framework presented in Section 3.3.2 is applied with the aim of identifying the best combination of source and site controls to complement the regional control to support the strategic objective of improving water quality in the Caw Burn.

Stage 1: Establishment of environmental standards and attenuation objectives

The environmental standards for good and high ecological status are determined using the Table 2-1. Based on this, a threshold of 25mg.l^{-1} for TSS was adopted as the target to reach good ecological status. Regarding TP, concentration thresholds of 0.05mg.l^{-1}

and $0.120mg.l^{-1}$ are required to achieve good and high ecological status respectively. Similarly, ammoniacal nitrogen concentration of $0.3mg.l^{-1}$ and $0.6mg.l^{-1}$ are necessary to achieve high and good ecological status respectively. Ammoniacal nitrogen recommendations are not taken into account for the design of retrofit solutions as a different approach regarding nitrogen is adopted in Section 3.3.2.

Stage 2: Determination of the partition of the roles between the source/site controls and the regional control

Regarding the Houston Industrial Estate, the level to which the regional control should contribute to water quality benefits is defined by the existing situation. As reported in Section 5.2.4, the regional control reduces the concentration of TSS and TP to $70mg.l^{-1}$ and $0.168mg.l^{-1}$ respectively. Implementation of source/site controls should reduce these concentrations below the environmental standards thresholds defined in Stage 1 to complement regional control water quality benefits.

Stage 3: Determination of socio-economic impacts and selection of the best treatment strategy

Based on the investigations reported in Chapter 5, key treatment trains are selected and Stage 3 of the framework is applied to estimate the associated costs. Key to the calculation of the costs is the determination of how SuDS implementation impacts on further development. In this precise case, the development of ponds within private curtilage is considered as having a significant impact on the potential for further development. This drawback is considered to be equal from site-to-site across the development and to impacts equally on the stakeholders vested in land and cost management. Following these considerations, the value "α" (Equation 6-1) has been chosen equal to 1 for all the SuDS ponds considered. Assuming the following:

- a market value (MV) of $900k£.ha^{-1}$ (Valuation Office Agency, 2010a);
- a capitalisation rate of 8% (expert guidance);

Equivalent costs for the selected treatment trains are estimated and summarised in Table 6-1.

Reference	Number of SuDS ponds	Area of pervious pavement (Ha)	Land take (m^2)	Cost (k£)	Equivalent costs (k£)
1	0	0	0	0	0
2	0	20	0	1200	1200
3	0	40	0	3000	3000
4	2	0	2500	800	1255
5	2	20	2500	3200	3655
6	2	40	2500	4600	5055
7	4	0	40000	1400	8684
8	4	20	40000	4000	11284
9	6	0	55000	2100	12100
10	6	20	55000	4500	14500
11	8	0	60000	2500	13430
12	8	20	60000	4600	15530

Table 6-1: Equivalent cost of selected treatment trains

The equivalent costs calculated are then benchmarked against quantitative performance of the different treatment trains on Figure 6-3, Figure 6-4 and Figure 6-5.

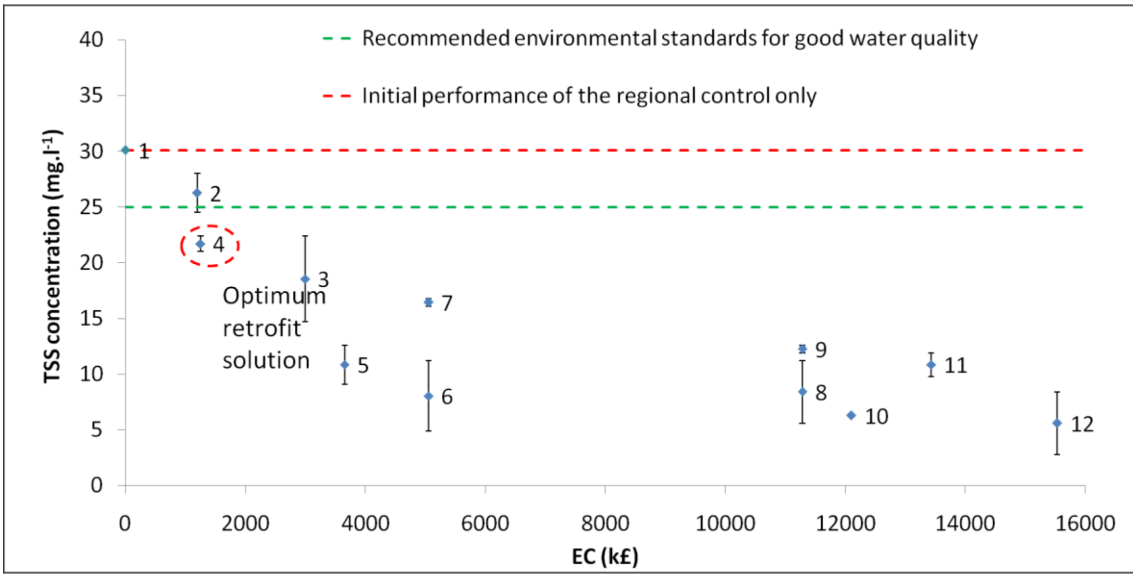

Figure 6-3: TSS concentration against equivalent costs for key treatment trains

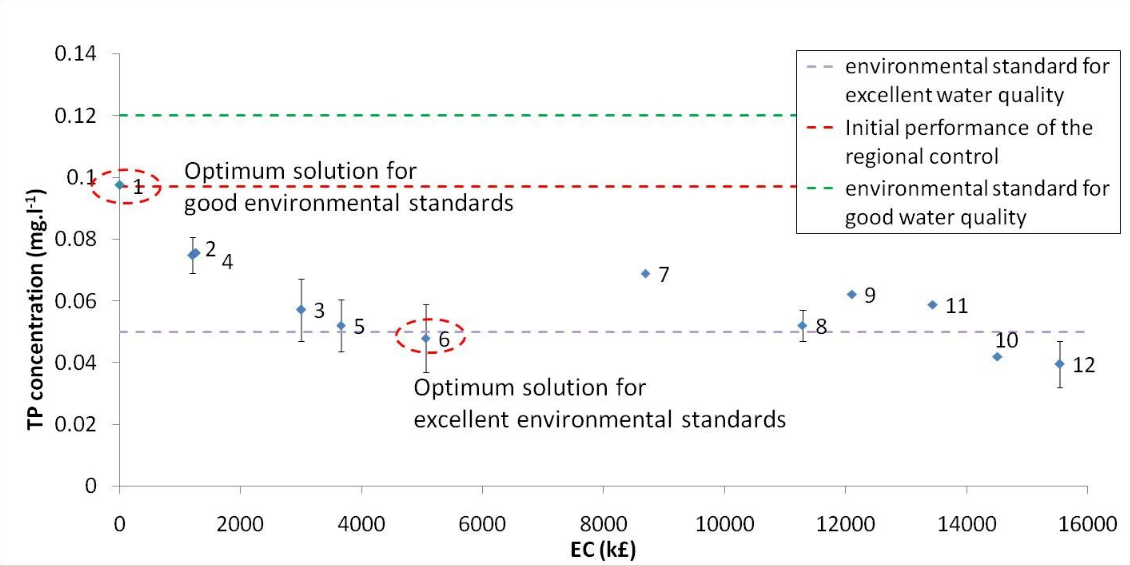

Figure 6-4: TP concentration against equivalent costs for key treatment trains

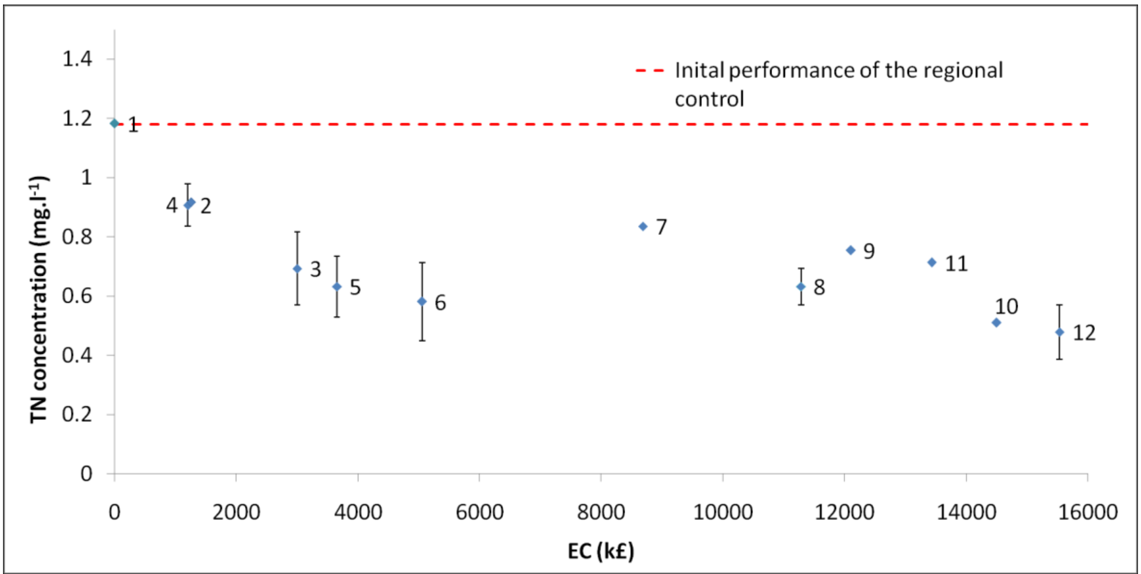

Figure 6-5: TN concentration against equivalent costs for key treatment trains

Analysis of Figure 6-3, Figure 6-4 and Figure 6-5 highlights five key factors:

- The charts allow the performance of the selected treatment trains to be compared with environmental standards. It is clear that each of the options considered, if implemented, would result in a significant improvement in outflow quality,
- The retrofit of the two best performing ponds identified in Chapter 5 is theoretically sufficient to limit the discharge below the threshold of 25mg.l^{-1} for TSS. Similarly, the retrofit of 2 ponds associated with 40 ha of pervious pavement (Section 5.2.2) is sufficient to reach high environmental standard for TP.

- It should be noted that the regional control is sufficient to reach good environmental standard for the phosphorus, the more stringent condition being on TP.
- Significant benefits can be achieved and both good and high ecological status for the receiving watercourse can be reached. Thus, the treatment train encompassing the retrofit of 2 ponds is sufficient to reach good ecological status, but the treatment train encompassing the retrofitting of 2 ponds and 40 ha of pervious pavement is the best solution to reach high ecological status for the receiving water course.
- Dominant solutions and non-dominant solutions were determined and underline that the retrofit of pervious pavement to a large extent (solutions 3,5 and 6) is at a lower equivalent cost than the retrofit of SuDS ponds (solutions 7,8 and 9) while achieving similar performance. This reflects high land value and the drawbacks associated with land sterilisation when retrofitting ponds.

Stage 4: Determination of socio-economic impacts and selection of the best attenuation strategy

As demonstrated in Chapter 5, the retrofit of ponds and pervious pavement can contribute significantly to the attenuation of the runoff in addition to their benefits in terms of water quality. Whether this attenuation should be complemented with supplementary attenuation is a decision made by the planning authority in consultation with key stakeholders. If necessary, attenuation can be provided using sub-surface storage or a modification of the regional control (Heal et al., 2005a). The retrofit of underground storage has a high economic cost in comparison with the enlargement of the regional control. Furthermore, due to its location, the additional land take associated with the modification of the regional control would have no impact on further development. Consequently, attenuation at the regional control, if necessary, is the best solution.

Stage 5: Proposition to reduce regional control land take

As the regional control already existing, this option is not further considered.

Stage 6: Final decision

Application of the framework allowed the determination of the best option for the retrofit of source and site controls at the Houston Industrial Estate. The retrofit of 2 ponds and 40 ha of pervious pavement provides treatment complementary to the existing regional control to meet discharge standards supporting high ecological status for the receiving water body. The presented solution optimises land take and cost impacts from the point of view of the developer and/or land owner. If necessary, attenuation provided by source and site control will be complemented at the regional control by an increase in the temporary storage available.

6.2.2 APPLICATION TO DALMARNOCK ROAD AREA CASE STUDY.

Investigations presented in Chapter 5 have underlined that a wide variety of SuDS solutions were available to be implemented at the site. These solutions can usefully complement the benefits provided by the planned regional control to support good or high ecological status in the receiving water body. In addition, the use of source and site controls can help in mitigating water quality risks at the regional control level and thus favour wildlife and biodiversity for this potentially desirable residential area (see Chapter 4). Finally, the benefits of source and site controls can be used to reduce the land take associated with the planned regional control to help secure a return on investment for developers in this location.

The framework is applied successively to the two situations according to the description provided in Section 5.1: the “realistic” case study where infiltration of runoff is prevented and the desktop case study where infiltration is encouraged.

6.2.2.1 Realistic case: Brownfield case study

This case assumes the site’s former use has contributed to leave contaminants into the soil. Consequently, infiltration of runoff into the soil can remobilised the contaminants and facilitate their migration to the groundwater. To prevent this situation, the use of infiltration techniques is formally prevented.

Stage1: Establishment of environmental standards and attenuation objectives

Table 2-1is used to determine the environmental standards for the River Clyde. The recommended environmental standard for TSS for the site is of 25mg.l^{-1}. Similarly, TP concentrations of 0.120mg.l^{-1} and 0.05mg.l^{-1} are recommended to contribute to a good or high status respectively for the receiving water body. Finally, ammoniacal nitrogen concentration of 0.3mg.l^{-1} and 0.6mg.l^{-1} are necessary to achieve good and high ecological status respectively.

Stage 2: Determination of the partition of the roles between source / site controls and regional controls

A peculiarity of the Dalamarnock Road Area is that the implementation of SuDS is considered at the design stage. Initial design of the regional control is undertaken accordingly with current recommendations for the design of regional controls (Scottish-Water, 2007). This design is subsequently reviewed while investigating impact of source and site controls on water quality in Stage 5.

Stage 3: determination of the socio-economic impacts and selection of the best treatment strategy

Equivalent costs are calculated for each treatment train. In this case, the different SuDS considered impact differently on land take perception depending on the location considered. The development of water butts within private curtilage is not considered as impacting on further development and has thus been allocated an "α" value of "0". Similarly, development of a swale network in the low density area can be considered as having a lower impact on further development than the land take of regional control for this case study. Based on discussion with stakeholders, proposed "α" values are determined and reported in Table 6-2.

SuDS type	α
Regional pond (RP)	1
Water Butt (WB)	0
Concrete Block Pavement (CBP)	0
Green Roof (GR)	0
Underground Storage (US)	0
Linear Wetland (LW)	0.7
Swales (SW)	0.6

Table 6-2: Adopted "α" values for the calculation of the equivalent costs of the treatment trains.

Associated with a land value of 1100k£.Ha^{-1} (Valuation Office Agency, 2010a), equivalent costs are determined and plotted against performance for the removal of different pollutants in Figure 6-6, Figure 6-7 and Figure 6-8.

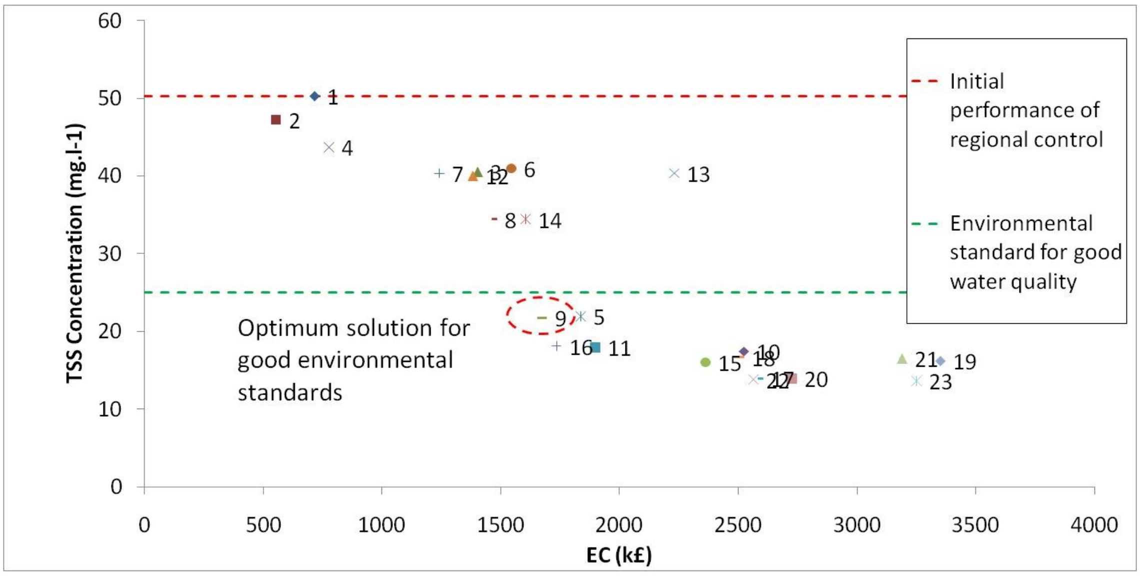

Figure 6-6: TSS concentration against equivalent cost.

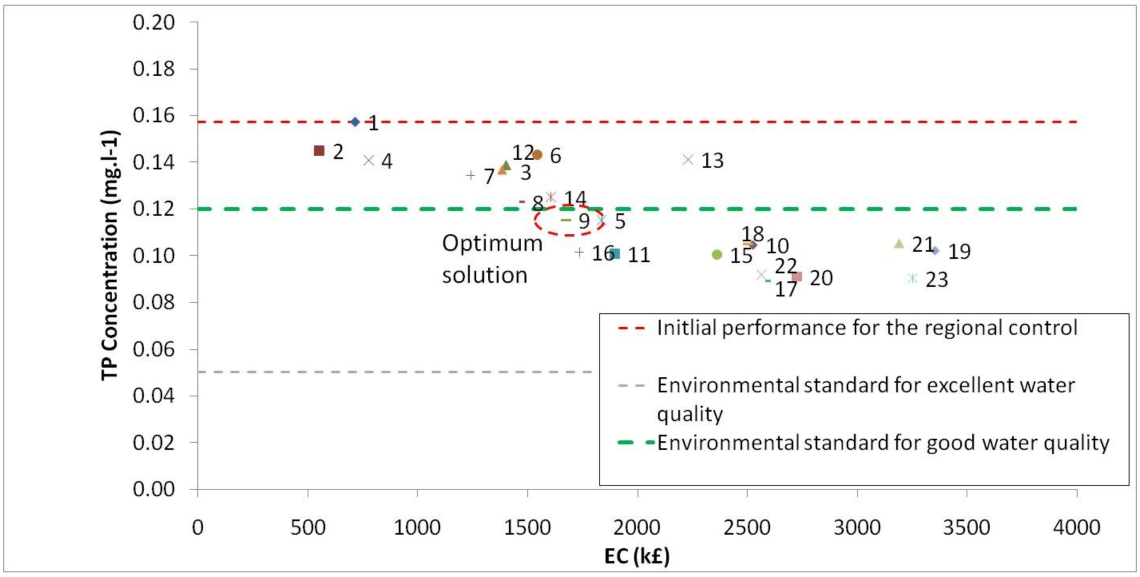

Figure 6-7: TP concentration against equivalent cost

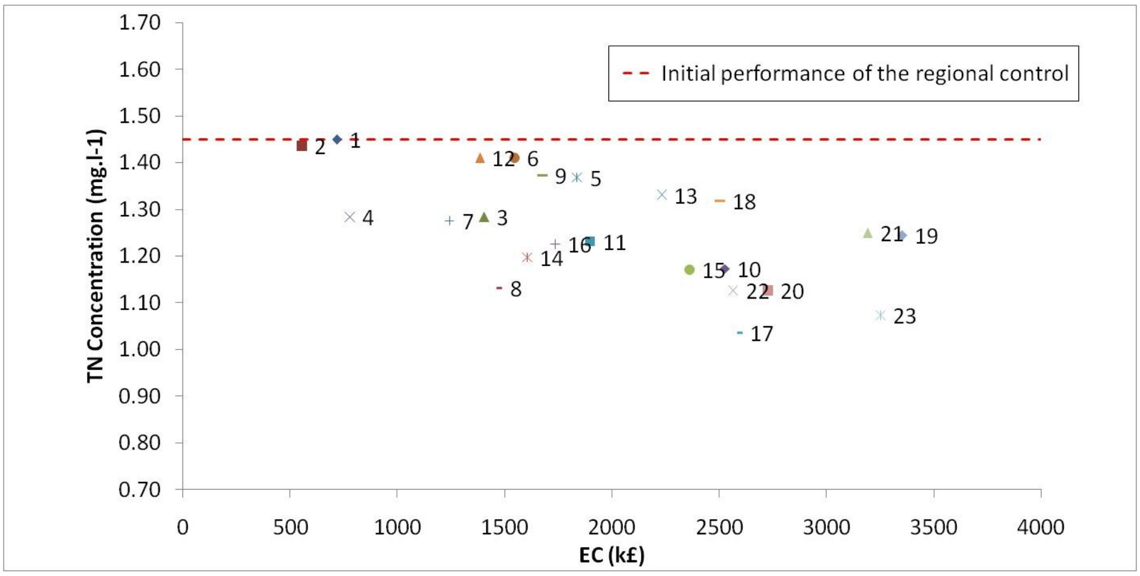

Figure 6-8: TN concentration against equivalent cost

The figure allows the identification of dominant and non-dominant solutions. The dominant solutions are compared against the environmental standards identified in Stage 1.

Figure 6-7 indicates that excellent environmental standards cannot be reached for TN using the current design of the regional control and associated source and site controls. However, good environmental standards, corresponding to the objectives set for 2027, can still be reached with the treatment train 9, which encompasses a linear wetland, green roofs in high density areas and a regional control. Similarly, this treatment train is also the best for managing TSS discharges concentrations below the environmental standard threshold.

Stage 4: Determination of the socio-economic impacts and the selection of the best attenuation strategy

Although the solution selected in Stage 3 provides some attenuation, more may be required by the environmental regulator and local authority. As outlined in Chapter 5, additional storage for the attenuation of medium to high return period runoff can be provided using sub-surface storage or the regional control. The two options are considered:

- Option 1: Construction of a pond with dedicated storage volume to complement attenuation provided by source and site controls. Alternatively, a basin, in addition to the pond providing water quality benefits and the last control before runoff is discharged could also have been considered. However, it is clear that this option would have been more costly and would have taken more land than the development of the pond with dedicated storage. Consequently, this alternative has not been considered any further.

- Option 2: Construction of sub-surface storage to complement attenuation provided by source and site controls.

Equivalent costs for the two options are calculated for attenuation of medium and high return period in Table 6-3.

	Pond supplementary area (m^2)	Pond whole life costs over 50 years (k£)	Sub-surface storage whole life costs over 50 years (k£)	Total Equivalent cost (k£)
30 years return period attenuation				
· Option 1	1128	269	0	514
· Option 2	289	215	415	694
100 years return period attenuation				
· Option 1	1616	289	0	649
· Option 2	289	215	636	915

Table 6-3: Equivalent costs comparisons

Based on equivalent costs reported in Table 6-3, the attenuation at the regional control level has a lower equivalent cost than the attenuation using sub-surface storage for any of the return periods considered. Considering the current land value, the construction of sub-surface storage does not justify the potential land saving at the regional control. Consequently, attenuation at the regional control level is considered the best option for attenuation of any return periods.

Stage 5: Proposition to reduce regional control size

As reported in Chapter 3, interviews with the stakeholders involved in SuDS implementation at the Dalmarnock Road site underlined the importance accorded to regional control land take. By considering current requirements for the design of regional controls, it is possible to reduce the land associated with the regional control based on water quality benefits of the source and site controls. Chapter 5 outlines these opportunities and has shown that significant reductions could be achieved whilst maintaining the concentrations of key pollutants below environmental standard thresholds. In some cases, the regional control could virtually be removed from the treatment train. While this option is not recommended, significant reductions of the regional control can be considered. However, these reductions should be seen within the context of increased overall land take and costs associated with the deployment of source and site controls.

Based on these results, the impact of regional control reduction on equivalent costs is investigated by reapplying Stage 3 of the framework. The recalculated equivalent costs are reported in Table 6-4.

Reference	Treatment train	land take savings (m²)	Initial equivalent cost (k£)	Recalculated equivalent costs (k£)
5	RP LW	200	1836	1792
9	RP LW GR	450	1674	1574
10	RP LW CBP	1200	2523	2256
11	RP LW WB	850	1897	1708
15	RP LW GR CBP	1200	2361	2094
16	RP LW GR WB	850	1735	1546
17	RP LW CBP WB	1800	2584	2184
18	RP SW LW GR	1600	2502	2146
19	RP SW LW CBP	1600	3352	2996
20	RP SW LW WB	2200	2726	2237
21	RP SW LW GR CBP	1600	3190	2834
22	RP SW LW GR WB	2200	2563	2074
23	RP SW LW GR CBP WB	2200	3250	2761

Table 6-4: Recalculation of equivalent costs for reduced treatment trains

The treatment trains presented in Table 6-4 have similar performance characteristics with respect to the removal of TSS and TP corresponding to the environmental standard for good ecological status. Consequently, the treatment train 16, due to it having lowest equivalent cost is the dominant solution. This treatment train, incorporating a linear wetland, green roofs for the high density area, water butts for the low density area and a regional control, allows a reduction in the regional control's land take allocated to the permanent pool by 850m^2.

Stage 6: Final decision

The application of the framework allows the selection of the treatment train incorporating a linear wetland, green roofs in the high density area, water butts in the low density area and a regional control as the best solution to keep discharges of pollutants below the environmental standards thresholds for good ecological status of the receiving water body. This solution should be complemented, if necessary by attenuation at the regional control level and thereby increasing its land take. However, significant land savings can be achieved based on water quality benefits provided by source and site controls, especially the linear wetland. The recommended reduction of the regional control size is of 850m^2, based on threshold concentrations to reach good environmental standard.

6.2.2.2 Desktop case study: Greenfield

As with the realistic case, the possibility of implementing a treatment train at the Dalmarnock road area is investigated assuming the site is a greenfield development. This assumption is based on the fact that, to date, no formal investigation of the pollutants contained within the soil has been undertaken. While investigations should be conducted before the site is developed, if this hypothesis is verified the opportunities to implement SuDS will increase as will the opportunities to reduce regional control land take as investigated in Section 5.1.4.2.

The framework developed is applied as it was to the greenfield case study.

Stage 1: Establishment of environmental standards and attenuation objectives

The environmental standards determined for the realistic case remain identical for the desktop case study. These environmental standards include:

- a TSS concentration below 0.25 mg/l, and;
- a TP concentration below 0.120 mg/l to reach good environmental standards and below 0.05mg/l to reach excellent water quality standards.

Stage 2: Determination of the roles between source/ site controls and the regional control

Similarly to the realistic case study, the partition between the role of the source/site and regional control are determined by Scottish Water standards. These recommendations are reviewed in Stage 5 to understand how regional control size can be reduced based on source and site controls performance.

Stage 3: Determination of socio economic impacts and selection of the best treatment strategy.

The determination of the equivalent costs for the desktop case study follows similar assumption that for the realistic case study. In particular, land value and capitalisation rate are assumed to be identical. Based on a discussion with the stakeholders, α values have been determined and are presented in Table 6-1.

SuDS type	α
Regional Pond (RP)	1
Soakaway (So)	0
Concrete Block Pavement (CBP)	0
Green Roofs (GR)	0
Infiltration Trenches (IT)	0.4
Swales (SW)	0.6

Table 6-5: Proposed α values for the desktop case study

The Figure 6-9, Figure 6-10 and Figure 6-11 present the performance of the different treatment trains against their equivalent costs calculated according to the methodology presented previously.

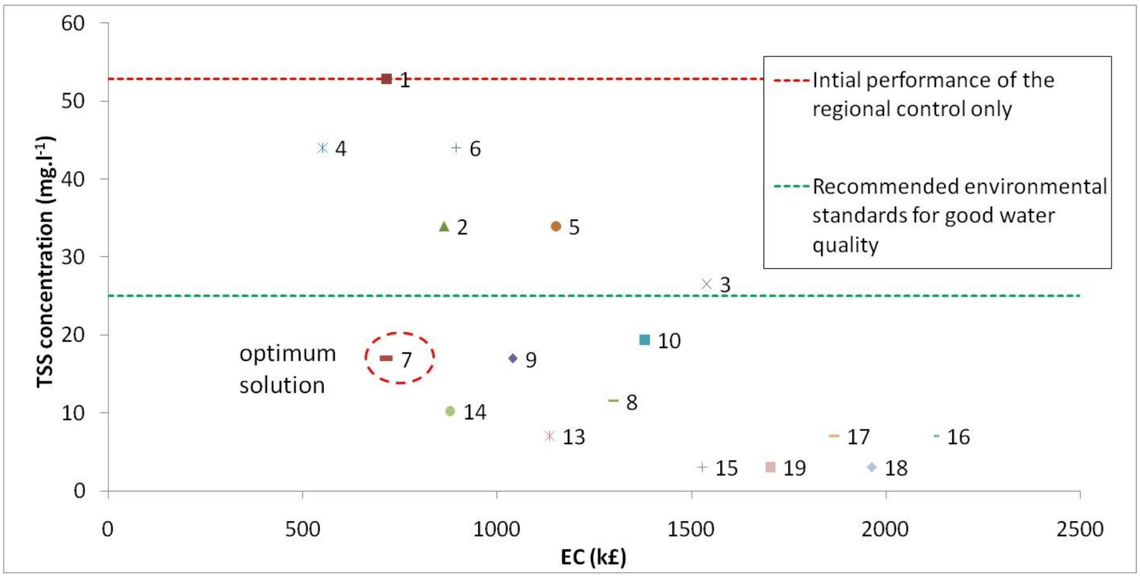

Figure 6-9: TSS concentration against equivalent cost

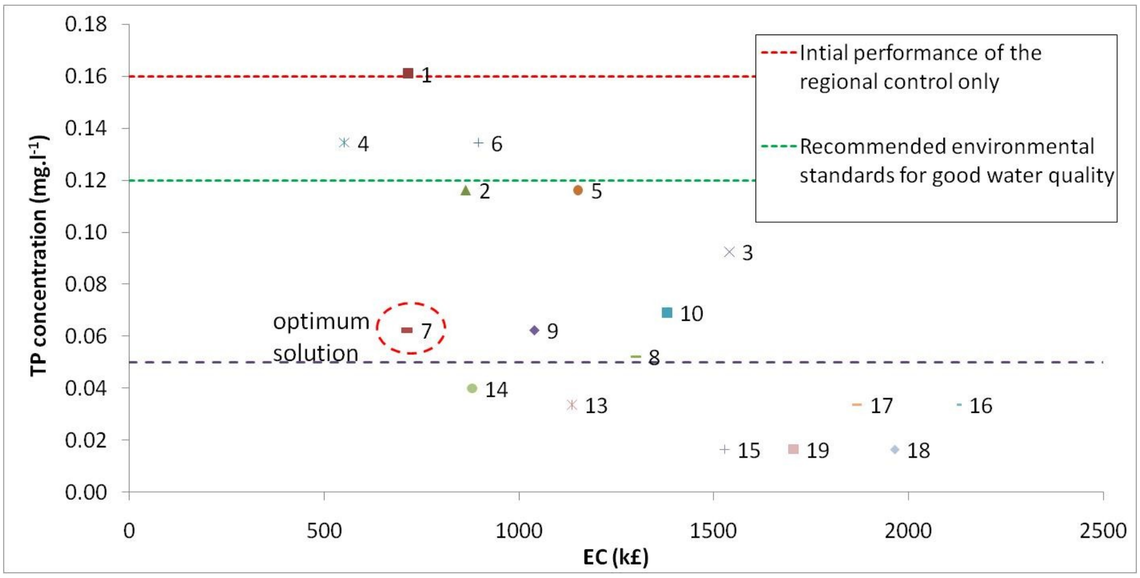

Figure 6-10: TP concentration against equivalent cost

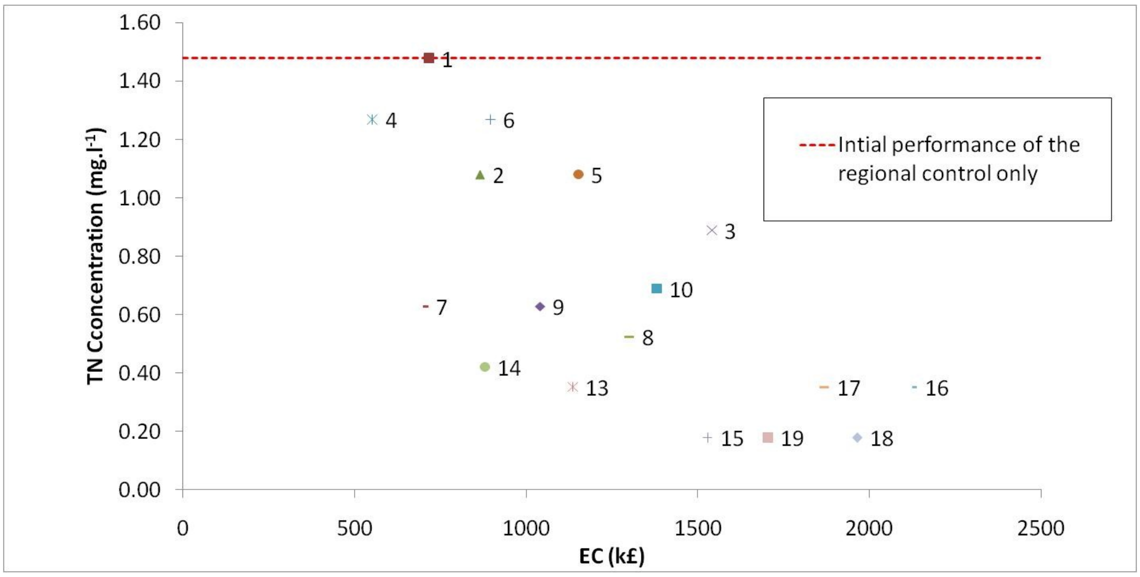

Figure 6-11: TN concentration against equivalent cost

The presented Figures highlight several points:

- The use of the treatment train number 7, including the use of infiltration trenches and green roofs in addition with the regional control, is sufficient to satisfy environmental standards for TSS.
- The treatment train number 7 is also the best option to reach good environmental standards for TP.
- Contrary to the realistic case study, the use of infiltration techniques can be used to reach excellent environmental standards for TP. This is achieved by using the treatment train number 14, which makes use of soakaways in the low density area in addition of the techniques used to satisfy good environmental standards.

This better removal for TP is achieved through infiltration of small rainfall events, conveying most of the pollutant load into the ground. This infiltration prevents pollutants within urban runoff to be conveyed further downstream to the receiving water course and thus provide significant water quality benefits.

Stage 4: Determination of socio economic impacts and selection of the best attenuation strategy.

Complementary attenuation for 30 years and 100 years is provided either at the regional control (option 1) or using underground storage (option 2). Effectiveness of both options is compared by recalculating equivalent costs of the treatment trains for both options. The results are presented on Table 6-6.

Reference	Treatment train	30 years		100 years	
		Option 1 (K£)	Option 2 (K£)	Option 1 (K£)	Option 2 (K£)
1	RP	1196	1728	1298	2096
2	RP IT	1218	1348	1319	1704
3	RP SW	1919	2072	2020	2560
4	RP GR	981	1584	1083	1952
5	RP CBP	1581	1532	1683	1388
6	RP SO	1325	1532	1427	1840
7	RP IT GR	1003	1204	1129	1560
8	RP IT CBP	1603	1152	1704	996
9	RP IT SO	1343	1152	1444	1448
10	RP SW GR	1708	1928	1809	2416
11	RP SW CBP	2355	2072	2456	1852
12	RP SW SO	2099	2072	2200	2304
13	RP IT GR CBP	1388	1008	1490	852
14	RP IT GR SO	1132	1008	1234	1304
15	RP SW IT GR	1730	1548	1831	2024
16	RP SW IT CBP	2326	1692	2478	1460
17	RP SW IT SO	2070	1692	2222	1912
18	RP SW IT GR CBP	2166	1548	2267	1316
19	RP SW IT GR SO	1906	1548	2007	1768

Table 6-6: Recalculated equivalent costs (grey shading indicates the lowest EC)

The table indicates that the option to follow varies depending on the treatment train considered and the return period to be attenuated.

In the case where option 7 is considered, attenuation at the regional control is preferred over attenuation using sub-surface storage as it has higher equivalent costs. However, if the treatment train number 14 is preferred by the environmental regulator, the use of sub-surface storage to provide attenuation for the 30 years return period event is preferred. The trend changes for higher return period and attenuation at the regional control is preferred for the 100 years return period.

Stage 5: Proposition to reduce regional control size

Based on the benefits provided by upstream controls and if treatment trains provided a treatment beyond the environmental standards proposed for TSS, the size of the regional control is reduced. Recalculated equivalent costs for these treatment trains are summarised in Table 6-7.

Reference	Treatment train	Land take savings (m^2)	Initial equivalent costs (k£)	Recalculated equivalent cost (k£)
7	RP IT GR	1500	700	367
8	RP IT CBP	2200	1300	811
9	RP IT SO	1500	1040	707
10	RP SW GR	800	1380	1202
13	RP IT GR CBP	2200	1136	647
14	RP IT GR SO	2200	880	391
15	RP SW IT GR	2200	1528	1039
16	RP SW IT CBP	2200	2124	1635
17	RP SW IT SO	2200	1868	1379
18	RP SW IT GR CBP	2200	1964	1475
19	RP SW IT GR SO	2200	1704	1215

Table 6-7: Proposition to reduce regional control land take and recalculated equivalent costs

Significant reductions of regional control land take are achievable. In the case the treatment number 7 is selected based on its performance and equivalent costs, a significant reduction of the regional control land take of 30% is achievable.

Stage 6: Final decision

Depending on environmental regulator’s need to reach good or excellent environmental standards, two treatment trains have been selected:

- In addition to the regional control, the use of infiltration trenches in the medium density area and green roofs in the high density area are sufficient to reach good environmental standards.

- In addition to the SuDS previously described, the implementation of soakaways in the low density area would support enhanced water quality benefits sufficient to reach excellent water quality standards.

If attenuation is deemed to be necessary, attenuation at the regional control scale or using sub-surface storage is necessary. The best option depends on the case considered:

- In cases where good environmental standards are to be reached, attenuation at the regional control is to be preferred.
- In cases where high environmental standards are to be reached, using sub-surface storage to attenuate the 30 years return period is the best option whereas, using the regional control is preferred to attenuate 100 years return period.

The water quality benefits achieved with the use of upstream SuDS control can be used to lead to significant land take reduction of the regional control. Based on TSS standards for good environmental status, a reduction of 30% of the regional control land take is possible.

6.3 CONCLUSIONS

Applying the treatment train philosophy has a non-trivial impact in terms of costs and land take that needs to be understood by stakeholders. The case studies underlined that selection of SuDS treatment trains can differ significantly from one site to another, reflecting land use, local and regional conditions and whether the area is already developed or not. The novel approach proposed, focusing on the development of a treatment train differs significantly from current practice focusing on end-of-pipe systems and increase drastically the number of solutions that could potentially be implemented. In order to identify the best option, an innovative framework was developed considering different options for source and site controls to complement regional controls and assess them in terms of their performance and impacts to select the most appropriate solution. Demonstration of the flexibility and adaptability of the framework was undertaken by applying it to three different cases studies. With different initial conditions, the framework has successfully allowed the identification of the best option for the drainage of urban runoff and provided a strong alternative to current practice.

The application of the framework should be seen within the context of the value associated with land and how this has been moderated depending on the location of the

SuDS within the urban fabric. Beyond the fact that refinement of the attribution of "α" values is desirable, it underlined the need for a concerted discussion amongst stakeholders with interests in costs and the land take of the project.

(Queensland Legislation, 2009; US Senate, 2002; European Communities, 2000)

Chapter 7 - CONCLUSIONS AND DISCUSSION

7.1 OVERVIEW OF THE PRESENTED RESEARCH

Within the context of recent flooding and degradation of water bodies leading to losses of biodiversity, concerns have been raised regarding existing water management schemes. Although recent changes in urban drainage have been made, evolving from the "all pipe" technique to the use of separate systems incorporating SuDS for the most recent developments, environmental drawbacks associated to urban growth and industrialisation remain a problem.

In parallel, economic and land constraints accelerate the losses of green spaces and associated biodiversity in cities. This is despite the latter having been shown to impact health and wellbeing of residents living in close proximity and are known to increase the value and saleability of surrounding properties.

Within this context, implementation of SuDS treatment trains within large residential and industrial catchments can offset the adverse effects of urbanisation and industrialisation by providing water quality and quantity benefits while procuring amenity and safeguarding biodiversity. However, despite guidance and environmental regulator recommendations on the use of SuDS in series, developers remain reluctant to implement treatment trains.

The objective of the presented research was therefore to develop a framework which may be used by the environmental regulator to optimise treatment train implementation within large residential and industrial catchments while safeguarding stakeholders' interests. The development of the framework comprised several key steps.

The first stage was to determine why, despite the contemporary guidance and recommendations available at the time, treatment trains were seldom implemented in Scotland and elsewhere. This objective has been met through structured interviews with key stakeholders involved in SuDS implementation. This highlighted that although perceived water quality, quantity and amenity improvements were clear, land take and costs were the primary barriers to SuDS uptake.

In parallel, while stakeholders advice was sought, the second stage was to determine if treatment train implementation would be received positively. In order to meet this objective, the perception of residents living in close proximity to SuDS ponds were investigated through structured questionnaires. Overall, although other factors could contribute significantly to the overall perception (mainly design and maintenance), there was a correlation between public perception and observed wildlife. Although ponds investigated were not always part of a full treatment train due to the relatively low uptake in Scotland, link between treatment trains and wildlife has been demonstrated.

The third stage was to understand how benefits expected from treatment train implementation, including water quality and water quantity benefits, were related to the barriers identified by the stakeholders. To best understand how these were related, three key cases studies were investigated. The later demonstrated that benefits associated with the use of treatment trains should be seen within increase of costs and/or land takes although reduction of regional control is possible and could be seen by developers as a way to manage footprint differently within the project.

The three objectives being fulfilled, a framework devised from the perspective of the environmental regulator was developed. The proposed framework has the aim of:

- maximising SuDS benefits in terms of water quality;
- maximising SuDS benefits in terms of attenuation;
- optimising SuDS implementation within the urban fabric;
- providing amenity to the residents living in close proximity; and,
- optimising land take and cost management.

These aims were satisfied by proposing a framework where water quality and quantity objectives are set by the environmental regulator in the context of the receiving watercourse state and local objectives in terms of amenity and biodiversity. The choice over the SuDS due to be implemented is then adjusted by cost and land take constraints for and within the site under developer's and local authority guidance.

7.2 SUMMARY

The conclusions and findings of each chapter are summarised below.

Chapter 1

This chapter presented the development of urban drainage through time. It highlighted that, despite the progresses that has been achieved, current runoff management is still unsatisfactory in regards to the failure to achieve the potential benefits available through the use of a "treatment train" and that there is a need for a step change in how systems are designed.

Chapter 2

The main points drawn from the literature review are as follows.

The chapter reviewed water quality and hydrological impact of urbanisation on runoff. This highlighted that without any appropriate measures; urban runoff was responsible for water quality degradation of receiving watercourses and could cause flooding at downstream locations.

The potential impacts of urban runoff can be offset through the use of SuDS. SuDS allow for the management of urban runoff by providing attenuation, water quality treatment and provides amenity to residents, corresponding to the "SuDS triangle" philosophy. Benefits resulting from SuDS can be maximised by using them in series, "a treatment train", and this is recommended by environmental regulator. Key locations where it has been applied in Scotland have demonstrated to achieve significant benefits.

Current design, regulations and guidance for implementing SuDS in Scotland, are based on the "treatment volume" approach and the design of retention ponds. This approach clearly favours the development of "end-of-pipe" systems and is not consistent with environmental regulator objectives to implement treatment trains.

The chapter reviewed decision support tools available for the implementation of SuDS and highlighted that numerous hydrological, hydraulic and water quality models were available. Based on research objectives, software performance and availability, MUSIC and Infoworks CS are retained as the main packages used for the development of the presented research.

Chapter 3

Structured interviews with key stakeholders have allowed the barriers to SuDS implementation to be identified. Land take, adoption, costs associated with the construction and maintenance for SuDS, potential safety issues and the non integrated approach have been felt as the main barriers blocking SuDS uptake on top of the inappropriate legislation surrounding their implementation. This observation is made despite the water body and flood protection, amenity and biodiversity benefits which could be achieved by larger SuDS uptake.

Chapter 4

Chapter 4 presented a study of the potential amenity delivered by the use of SuDS regional controls. The investigation focussed on a survey of over 600 households across 6 catchments using a structured questionnaire. This research found that ponds and wetlands located in residential areas are valuable assets: despite health and safety issues were identified as the main drawback of living in close proximity to ponds by local residents, these are relatively low compared to other urban risks. Moreover, these issues were particularly felt at ponds designed to meet Scottish Water (2006) standards where extreme care is taken to avoid drowning accidents. The monetary value residents would eventually be willing to pay to live in close proximity to SuDS ponds varies between £3.2 and £25 per month with an average of £10.95 per month. The amount of money residents are willing to pay varies primarily as a function of the wildlife spotted in relation to the pond. This highlights the benefits use of upstream SuDS could provide in terms of improved habitat provision. It is hypothesised that considering an average payment of 10.95 per month, a relatively low dwelling density would be sufficient to compensate for costs of construction and maintenance of a standard pond. Although the sites studied were seldom part of treatment trains, residents highly valued SuDS as a key community asset. This aspect reinforces the need to use source and site controls upstream of regional controls so as to maximise water quality potential and the need for a different approach to managing risk perception.

Chapter 5

In Chapter 5 three Scottish cases studies located at two sites were presented. Based on this, the following conclusions may be drawn:

SuDS source and site controls implementation significantly increased whole life costs and/or land take of drainage systems compared with equivalent regional control performance (the exception being green roof systems).

The potential reduction of regional land take based on water quality and hydraulical performance of source and site controls provides the developer the opportunity to manage footprint differently. However, this should be seen in the context of an overall increase of costs of construction and maintenance and land take associated with SuDS at the development scale.

This chapter thus highlighted that changes to adoption schemes and/or water quality performance evaluations alone were unlikely to be sufficient to encourage a wider SuDS uptake as an alternative to hard engineering techniques.

Chapter 6

Chapter 6 provides the environmental regulator with a framework to facilitate SuDS treatment train implementation. The approach offers a mechanism whereby water quality objectives can be met whilst optimising other stakeholder needs such as footprint, flood risk and amenity. The framework is based on the following:

Catchment characteristics and land use are used to select SuDS techniques that could potentially be implemented;

Water quality and water quantity objectives are set out by the environmental regulator based on the environmental standards of the receiving watercourse and potential flooding issues at downstream locations;

Identification of the water quality benefits achieved by source/site and regional SuDS is defined by the environmental regulator based on the performance of the existing regional control and / or existing guidance regarding design of SuDS ponds and implementation of treatment train.

Best strategy to reach environmental regulator objectives is determined based on local authorities and developers appraisal of land use and costs of the selected SuDS.

7.3 RECOMMENDATIONS FOR FUTURE WORK

The work presented in this thesis provides a framework to improve drainage for large urban and industrial areas. The framework promotes the use of a treatment train, supported by the environmental regulator to improve water quality and quantity benefits while providing amenity to residents. However, full integration of treatment train in large developments needs to be supported by changes in current SuDS implementation process as follow:

Improving water quality assessment: the use of "Vt" is not consistent with SuDS performance to reflect water quality benefits. While strongly promoting the implementation of retention ponds used as "end-of-pipe" SuDS, other SuDS not incorporating a treatment train are seldom used. While this issue could be easily by passed for small catchment by the use of nomographs or decision tools similar to STTAT (Jefferies, 2009), large residential and industrial developments need a comprehensive approach to determine potential impact and investigate potential solutions to remediate water quality issues.

Changing adoption and/or funding schemes: SuDS to be adopted by Scottish water are limited to subsurface storage, retention and detention ponds designed to Scottish water standards. Changes in adoption or set up of funding schemes for alternative SuDS types would promote SuDS uptake. In particular, it has been shown that, following appropriate design and maintenance, SuDS were an added value for the community and a potential return on investment was possible.

In addition to the current limitations in SuDS implementation process, there are others on the horizon that need to be appreciated and that should, ideally, be addressed in future research. These include:

Investigating how land take and whole life cost compete in other environment: the current methodology investigated a limited number of case studies to determine how land take and whole life cost compete and was particularly looking at rather high land pricing. Investigations of other case studies, where land pressure is lower, would allow understanding how to balance land take and costs for SuDS and thus refine the determination and suggestion of "α" value. While any clear methodology is defined to determine "α" for other development types and location, local authorities and developers inputs are necessary to the application of the framework.

Investigating SuDS treatment train performances: the development of the current framework is based on individual SuDS performance reported in the literature, especially regarding water quality. The performance of treatment trains, due to their relatively low uptake, is determined based on the performance of individual SuDS. While treatment trains are due to be implemented in the coming future, the monitoring of runoff quality at the different stages would significantly improve general knowledge on treatment train performance. The result of the monitoring could help in improving the design of the current proposed framework.

APPENDIX A: QUESTIONNAIRE ON SUDS PUBLIC PERCEPTION

Part A: Introduction to your local pond

Rain water collected in drainage systems from household gutters/driveways and roads can contain pollutants for example salts, heavy metals and oils. These pollutants need to be treated or intercepted prior to discharging to a natural water course such as a burn or river. One such method is by the use of Ponds which can form part of a *sustainable drainage system*, commonly known as *SuDS*. In addition, ponds provide storage relief and significantly reduce risk of flooding to properties and roads from extreme storm events.

Q1) Did you realise that your local pond was capable of these functions?

☐ Yes, completely ☐ Vaguely aware ☐ I was unaware

Part B: Specific questions about your local pond

Q1) Was the pond in place when you moved to this area?

☐ Yes ☐ No (Go to question 3) ☐ Unsure

Q2) Would you say that the presence of the pond influenced your choice to move in this area in a positive or a negative way?

☐ Positive ☐ Negative
☐ No difference ☐ Unsure

Q3) Please rank from 1 to 5 the factors that influenced your choice of accommodation. (*with 1 as the most important and 5 as the least important)*

	1	2	3	4	5
The accommodation in itself (e.g. number of rooms, cost…)					
The location (e.g. proximity to work area, convenient bus service or facilities)					
The surroundings (e.g. visual aspect of the area, proximity to facilities)					
Other (please specify):………					

Q4) Please rank from 1 to 5 the factors you see as important to the neighbourhood. (*with 1 as the most important and 5 as the least important)*

	1	2	3	4	5
Safety of the area					
Proximity to facilities (school, shops…)					
Visual aspect of the neighbourhood					
Closeness to open or green spaces					
Other (please specify):………					

Q5) Overall, do you think the system is appropriately maintained?

☐ Yes ☐ No ☐ Unsure

Q6) Can you see the pond from one or more rooms of your home?

☐ Yes
Please specify the number of rooms view on the facility: …

☐ No (go to question 7)

☐ I don't know (please go to question Q7)

Q7) How well can you see the pond from your home?

☐ Very good
☐ Good
☐ Neutral
☐ Poor
☐ Very poor
☐ I don't know

Q8) Can you walk to your local pond?

☐ Yes
Please specify:
☐ Under 5 Mins

☐ Around 5 Mins

☐ Over 5 Mins

☐ I'm unsure

Q9) Please rank from 1 to 5 what you perceive the benefits of living close to a pond to be. (*with 1 as the most important and 5 as the least important)*

	1	2	3	4	5
Can be used as a pet walk					
Provides visual amenity to the area					
Provides biodiversity (plants and animals) to the surrounding area					
Sustainable drainage solution					
Educational purposes for children					
Adds to the value of homes.					
Other (please specify):………					

Q10 What do you perceive would be the dangerousness of living close to the following features compared to your pond?

	Less dangerous	The same	More dangerous	Unsure
Busy road				
Landfill site				
River				
Natural pond				

Q11) Please rank how natural you feel the pond looks (*with 1 as the most natural and 5 as the least natural)*

1	2	3	4	5

Q12) Please rank from 1 to 5 what you perceive to be the potential disadvantages of living in close proximity of a pond. (*with 1 as the most important and 5 as the least important)*

	1	2	3	4	5
Promotes vandalism					
Presents safety risks (e.g. for children)					
Source of flooding					
Accumulates litter					
Attracts insects					
Attracts rodents					
Aesthetically unpleasant					
Unpleasant smells					
Other (please specify):………					

Q13) Have you noticed any pollution in or close to the pond in the past year? (*Please tick the most suitable boxes below, one on each row*)

	Very often (> 20 times)	**Often** (10 to 20 times)	**Sometimes** (3 to 10 times)	**Rarely** (only once or twice)	**Never**	**I don't know**
Foam / scum						
Algae						
Litter (e.g. cans, paper…)						
Oil sheen						
Other (please specify): …………………………						

Q14) Have been able to spot any wildlife in or close to the pond in the past year? (*Please tick the most suitable boxes below, one on each row*)

	Very often (> 20 times)	**Often** (10 to 20 times)	**Sometimes** (3 to 10 times)	**Rarely** (only once or twice)	**Never**	**I don't know**
Small Birds (e.g. sparrow/ robin / tit)						
Large birds (e.g. ducks / geese / swans / herons)						
Insects (e.g. dragonflies / beetles / water bugs / grasshoppers)						
Reptiles (e.g. lizard)						
Amphibians (e.g. frogs/ salamanders)						
Mammals (e.g. hedgehogs / foxes)						
Other (please specify): …………………………						

Part C: Financial questions

Please note that this information will not be attributed to individual addresses, nor will it be passed on to any third parties. This information will be used for weighting the importance of SuDS to individuals. Money will never be requested from you as a result of completing this questionnaire.

Q1) Do you think benefits (if any) can offset the problems (if any) of living in close proximity to a pond and add value to the area?

☐ Yes ☐ No ☐ Unsure

Q2) If you have to move in another area where similar advantages to those of the pond can be provided, per month, how much would you be willing to pay:

☐ £ 0	☐ £ 30	☐ £ 60	☐ £ 90
☐ £ 5	☐ £ 35	☐ £ 65	☐ £ 95
☐ £ 10	☐ £ 40	☐ £ 70	☐ £ 100
☐ £ 15	☐ £ 45	☐ £ 75	☐ £ 105
☐ £ 20	☐ £ 50	☐ £ 80	☐ £ 110
☐ £ 25	☐ £ 55	☐ £ 85	☐ £ 115

Part D: Respondent demographic details

Please note that this information will not be attributed to individual addresses, nor will it be passed on to any third parties It will be used for purely statically purposes only.

Q1) How old are you?

☐ Under 18	☐ 45-54
☐ 18-24	☐ 55-59
☐ 25-34	☐ 60-65
☐ 35-44	☐ Above 65

Q2) Which of the three best describes your status?

☐ Tenant ☐ Owner ☐ Other

Q3) How many bedrooms do you have in your home?

☐ 1	☐ 3
☐ 2	☐ More than 3

...
....

Q4) ***Would you like to participate in the free prized draw to win £50. Simply provide us with your email or detailed address and we will inform the winner of the result on 1st of July 2009. (Please note <u>this section will held separately</u> from the survey)***

If you would like to receive details of the results at the end of this study, please tick the box below and include your contact details above (Please note your contact details <u>will not</u> go on any mailing lists)

☐ I would like feedback

Thank you very much for your time in participating in this survey.
! Please don't forget to send us your questionnaire to be entered into the prize draw!

APPENDIX B: PUBLISHED JOURNAL PAPERS

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Valuing amenity: public perceptions of sustainable drainage systems ponds

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Keywords
contingent valuation; drainage; residents' perception; SuDS.

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Abstract

Understanding the potential concerns and needs of residents is key to achieving good acceptability of sustainable drainage systems (SuDS). This paper highlights, through the application of a structured questionnaire, the potential value to residents of living in close proximity to a SuDS pond. The results show that although the pond's characteristics are not the main factor influencing the choice to move into an area, its effect is markedly positive. Contingent valuation of the benefits is used to show that the additional value brought by SuDS amenity, when monetised, can offset a pond's initial construction costs and ongoing maintenance, hence ensuring the return on investment for developers. By building on existing research, this paper highlights major changes in the perception and valuation of pond structures.

Introduction

Urban activities such as car driving (Napier *et al*. 2008), weeding gardens or bin cleaning (Campbell *et al*. 2006) are a source of pollutants that are deposited on urban surfaces and then subsequently washed off during rainfall events. Among the deposited pollutants, suspended solids, polycyclic acid hydrocarbons (PAHs), nitrogen, phosphorous and heavy metals have been reported as the most harmful to the environment because of their impact on wildlife and potential amenity of receiving watercourses (Eriksson *et al*. 2007). Additionally, the development of impervious surfaces reduces the time of concentration and the opportunity for runoff to infiltrate into the soil, which leads to increased runoff volumes and increased peak flows. These factors lead to negative impacts on watercourse morphology and potentially worsen downstream flood risk (e.g. Nirupama & Simonovic 2007). In order to mitigate the harmful impacts of urbanisation on the environment, treatment and attenuation of urban runoff using sustainable drainage systems (SuDS) has now been made compulsory for every new development in Scotland (HMSO 2005). SuDS techniques include a wide range of different tools (CIRIA 2007) that should be used in a series to treat and attenuate runoff to the required standard (SEPA 2006). Among the SuDS techniques available, ponds and wetlands, which include a permanent pool of water and vegetation, are regarded as having a high potential to be a source of biodiversity and amenity in urban development and help to improve health and well-being in cities (Pretty *et al*. 2007; Song *et al*. 2007; Velarde *et al*. 2007). The interests of stakeholders, including the environmental regulator and sewerage undertaker, to include SuDS in new developments are generally known (Wild *et al*. 2002) but the view of residents living in close proximity to SuDS is still not fully understood. This is key as positive public perception will ensure that ponds and wetlands satisfy not only water quality and water quantity objectives but bring amenity in developments according to the SuDS triangle (Bastien *et al*. 2010a, b).

SuDS public perception and contingent valuation (CV)

The public perception of SuDS structures has been investigated by other researchers: Yuen & Hien (2005) demonstrated that green roofs have a positive impact on residents in high-density areas. Similarly, the perception of rainwater harvesting by local residents was investigated by Ward *et al*. (2009), who demonstrated that residents were keen on re-using the water from their own roof but reluctant to recycle runoff from other sources. Whether it concerns aesthetics improvements, access and community benefits or potential for public education and awareness (Ellis *et al.* 2004; CIRIA 2007), the term amenity has often been used to characterise the potential benefits the residents could find in a project. With respect to retention ponds specifically, Apostolaki *et al.* (2006) summarised the results of door-to-door public perception questionnaires conducted at UK sites between 2000 and 2002 among residents adjacent to 10 ponds situated in Scotland, England and Wales. The survey was in the form of an open-ended questionnaire and aimed at assessing public perception of SuDS ponds, including potential benefits and disadvantages. Overall, the survey demonstrated that there was significant interest in ponds and suggested that the presence of a well-established pond was perceived as improving property saleability and value by around 10%. Within the context of current surface water management, where costs have been identified as one possible barrier for SuDS implementation (McKissock *et al.* 2003; Todorovic *et al.* 2008), it may be argued that charging residents a factoring fee, based on the additional value that pond amenity provides, could help to offset water management costs. Within this context, the work conducted in 2004 and presented by Apostolaki *et al.* (2006) has highlighted that an opportunity exists to offset SuDS costs with the benefits they provide to homeowners and residents.

Evaluating environmental goods in terms of monetary value has always been seen as a difficult task (Ebert 2008). However, two main techniques have emerged that allow their assessment: the hedonic valuation and the CV methods. Hedonic pricing relates to the observation of house price variations because of different factors. This approach has been used to investigate the economic value of urban green space in numerous surveys undertaken in high-density environments (Luttik 2000; Kestens *et al.* 2004; Kong *et al.* 2007) and has generally demonstrated the positive impact of green spaces on property value. Furthermore, the use of the method to value a detention basin associated with multipurpose green space found that the device had a positive impact on property values, while a detention basin without any green features was shown to have no discernable impact (Lee & Li 2009). Despite these results, the hedonic valuation of environmental benefits is not an easy exercise as it requires significant data on property values and the choice of variables selected by authors can appear to be quite subjective. In contrast, the CV approach consists of asking, through a structured interview, the price the respondent would be willing to pay for market or environmental goods. Compared with hedonic pricing, the CV method requires less data on the surroundings, but relies heavily on the respondents' willingness to participate. Despite this, it has been applied successfully to determine the value associated with environmental benefits (Arrow *et al.* 1993).

In summary, the work presented here aims to augment and update knowledge in this area of research by providing:

- an understanding of the benefits that ponds provide and an estimate of their perceived value to residents and homeowners and
- a comparison with the work previously undertaken, in particular, to understand how public perception has changed in the 7 years since the last detailed study was undertaken in the UK.

Methodology

An understanding of the benefits that SuDS ponds provide and an estimate of their perceived value to residents and homeowners were determined through the use of a structured questionnaire. The questionnaire objectives were:

- To identify how the presence of the pond influences people to move to an area.
- To understand public awareness of the pond and its SuDS function.
- To identify residents' perception of the pond, including perceived advantages, wildlife and disadvantages.
- To determine, through CV, the potential monetary value associated with the pond.

It should be noted that the term 'wildlife' is used here as residents could not reasonably be expected to provide a response that can be objectively used to quantify 'biodiversity'.

Once the questionnaire was constructed, a pilot survey was conducted using face-to-face interviews in May 2009 to identify and refine any unclear parts. The pilot questionnaire was trialled at two pond locations, with four interviews being conducted at each to ensure that the questions were understandable and that participants had sufficient information to answer questions. The refined questionnaire comprised four parts (McLoughlin 2009):

A. An introduction presenting SuDS.
B. Specific questions targeting pond perception from residents' point of view.
C. A financial part to establish the willingness to pay for any benefits associated with the pond.
D. Demographic questions and opportunity to participate in a prize draw.

The questionnaire was distributed among residents living near well-established ponds located in and around Edinburgh (Fig. 1). Although none of the ponds were part of a formal treatment train, their settings are quite different as reported in Table 1 and Fig. 2, where the key features of the ponds are presented.

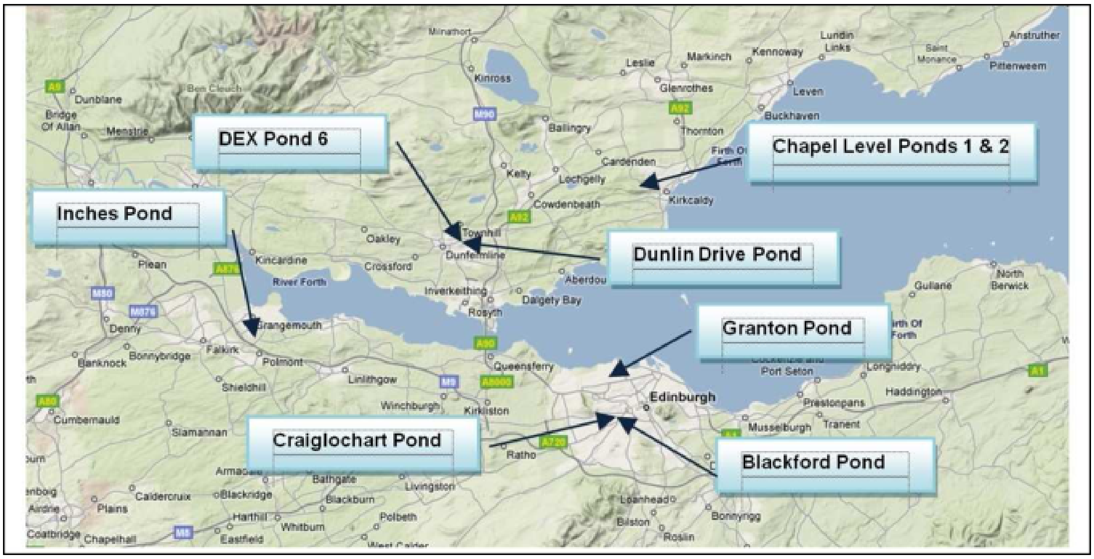

Fig. 1. Location of the eight ponds targeted in the survey.

Results and discussion

Respondents' demographic and location

To be eligible to receive the questionnaire, residents had to live within 5-min walk (400 m) of one of the selected ponds. This was to ensure that residents had ready access to the pond and that most of them would be aware of its existence. A total of 400 questionnaires were distributed to households in proximity of the eight selected ponds. Of the 400 issued, 108 questionnaires were returned, although some were not fully completed. One hundred and seven questionnaires were deemed to contain exploitable answers, and equates to an overall response rate (RR1) of 27% according to the AAPOR definition (The American Association for Public Opinion Research 2009). While the response rate may appear modest, these figures are in the range of what could have been reasonably expected in comparisons with previous surveys (Apostolaki *et al*. 2006). The response rate and sample size mean that the margin of error is $\pm 7.2\%$ at the 95% confidence level. Respondents' details may be found in Table 2. In contrast to earlier studies, 94% of the respondents stated that the pond was in place when they moved to the area.

To understand the social background of the responders, the Scottish Index of Multiple Deprivation (SIMD) (Scottish Executive 2009) was used. This uses 31 indicators such as income, employment and housing to classify over 6500 areas in Scotland as a function of their level of 'deprivation'. Apart from the Granton area, the SIMD database reports that the areas considered cannot be defined as 'deprived' – all are in the top 40%. Although the Granton pond is located in an area reported as being more deprived, it is newly established in a recently developed area and is likely to become a sought-after area in the next few years. Overall, the areas surveyed are likely to be populated by people from higher socio-economic groups. Indeed, the majority of the respondents were home owners aged between 35 and 45 years (64.6%).

The accommodation in context

When asked whether the presence of the pond affected their decision to move into an area, only 32% of the respondents said that it had a positive influence, whereas 66% claimed it did not make any difference and only 2% reported that it had a negative impact. These results must be treated carefully, as there was significant variation between sites. Indeed, for the same question, 63% of the residents adjacent to the Craiglockart pond reported that it had a positive influence, whereas for Inches pond 100% of the respondents said it made no difference. When asked to specify the factors influencing their decision to move to an area, the accommodation itself came first, with 72% of the respondents answering it is the most important, with location and surroundings achieving only 38 and 28%, respectively. When specifying important surrounding factors, respondents clearly indicated that a safe environment was the primary focus (Fig. 3). Secondary factors included access to facilities, visual aspect and importance of green space. When asked to detail how they considered the safety of a natural pond compared with other urban infrastructure, roads and rivers were both considered as being more dangerous (Fig.

Table 1 Pond details

Location	Draining area	SuDS type	Approximate pond size (ha)	Functions	Construction period (circa)	Ownership and maintenance responsibilities	Access to the water body	Additional amenity features
Inches Pond, Larbert	Residential roofs and roads	Detention pond	~0.05	Attenuation and treatment	2000	Scottish Water	Very limited with fencing and reed beds	Path along the pond
Chapel Level Pond 1, Kirkcaldy	Residential roofs and roads	Detention pond	~0.5	Attenuation and treatment	2005	Scottish Water	Double fencing, bushes and reeds	None
Chapel Level Pond 2, Kirkcaldy			~0.5					None
DEX Pond 6, Dunfermiline	Residential roofs and roads	Three linked detention ponds	~0.5	Attenuation and treatment	2005	Scottish Water	Very limited with fencing and reed beds	Path around the pond
Dunlin Drive Pond, Dunfermline	Several hundred houses and access roads	Detention pond	~0.5	Attenuation and treatment	2005	Scottish Water	Limited with fencing	None
Granton Pond, Edinburgh	Commercial development	Detention pond and wetland	~0.5	Recreational, attenuation and treatment	2008	Private	Limited with low height vegetation	Pond integrated to a park. Path along the pond with a bridge across the water
Craiglochart Pond, Edinburgh	One large building and access roads	Pond	~1	Recreational	1878	Edinburgh Council	No restrictions	Pond integrated in the border of a forest. Include a path along the pond
Blackford Pond	Roads only	Pond and wetland	~0.8	Recreational and ecological	1848	Edinburgh Council	No restrictions	Pond integrated in the border of a forest Include a path along the pond

Fig. 2. (a) Blackford pond, (b) Chapel Level 2 pond, (c) Dex pond 6, Dunfermline, (d) Chapel Level 1 pond, (e) Granton pond, Edinburgh, (f) Dunline drive pond, (g) Inches pond, Larbet and (h) Craiglochart pond, Edinburgh.

Table 2 Demographic and location characteristics of the survey respondents (%) ($n = 107$)

Age (%)	Location (%)	Situation (%)
< 18 (1)	Blackford Pond (18)	Tenant (8)
18–24 (0)	Chapel Level Pond 1 (10)	Owner (92)
25–34 (8)	Chapel Level Pond 2 (13)	
35–44 (32)	Craiglochart Pond (19)	
45–54 (32)	DEX Pond 6 (10)	
55–59 (7)	Dunline Drive Pond (9)	
60–65 (5)	Granton Pond (5)	
> 65 (12)	Inches Pond (16)	
NA (2)		

4). This is an important point as the potential health and safety risks posed by SuDS ponds, despite the inclusion of low slopes, barriers and planting, must be placed within the context of that presented by other elements of urban infrastructure. This point has also been noted for other risks posed by urban drainage infrastructure (Arthur *et al*. 2009).

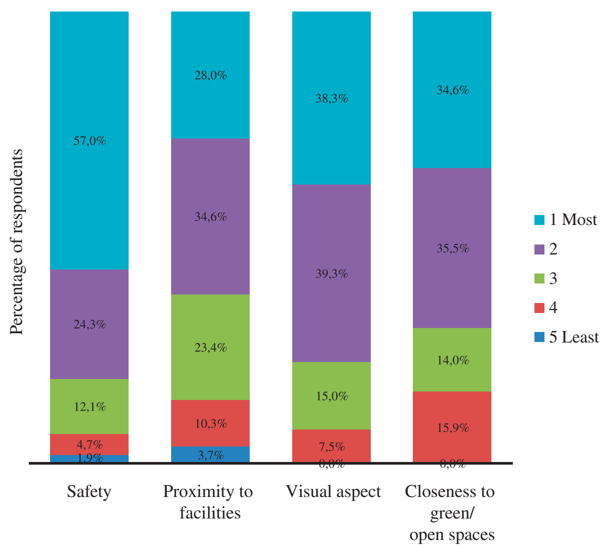

Fig. 3. Important neighbourhood factor.

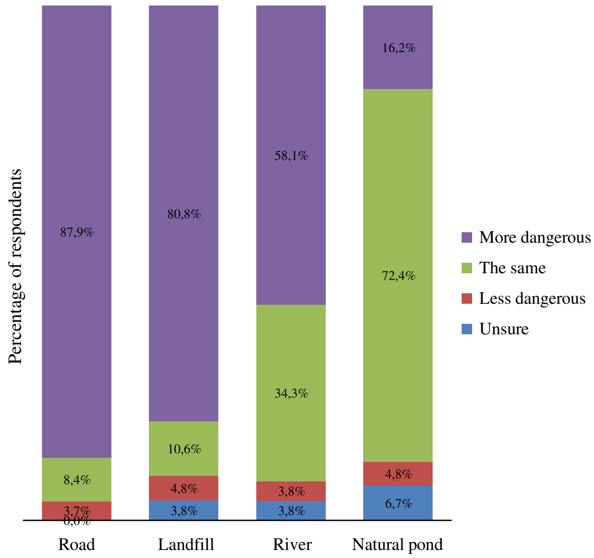

Fig. 4. Safety perception.

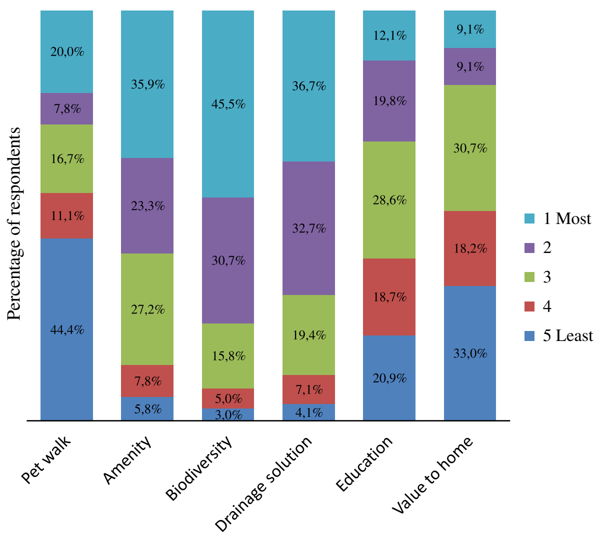

Fig. 5. Most important benefits of living close to a pond.

Pond perception

The second part of the questionnaire was concerned with identifying how the public perceived the pond – either in a positive or a negative way.

Advantages

Regarding the benefits provided by the pond, the perception of wildlife, in the form of a number of wild species identified by the residents, achieved top ranking, with 76.5% of the respondents identifying it as the most important benefit (Fig. 5). Any additional value provided to their home by the pond was not considered by the respondents as this achieved

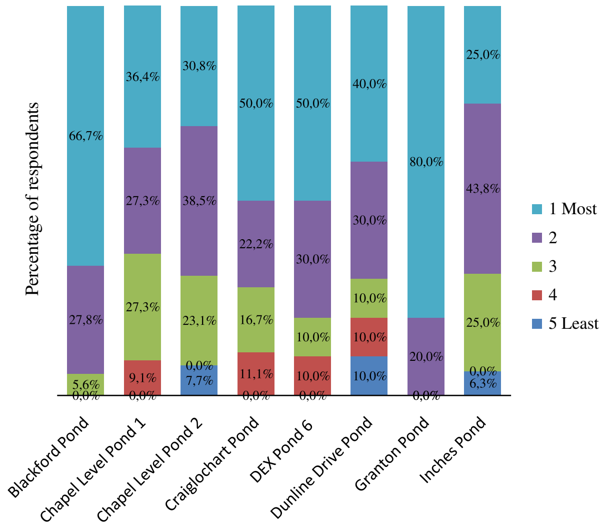

Fig. 6. Perception of sustainable drainage system (SuDS) as a primary wildlife-enhancing measure.

the lowest ranking. These results are largely site specific as Blackford and Granton ponds achieve a high ranking regarding wildlife, with 84 and 100% of the respective respondents mentioning it as the most important function (Fig. 6). The majority of the respondents (74%) claimed that they were aware that the pond is able to perform as an SuDS (i.e. treating pollution and attenuating the flow). This high level of awareness of ponds' function was confirmed when residents were questioned on the potential benefits – drainage solution was the second answer given, with 69% considering that it was important (Fig. 5).

Disadvantages

As demonstrated previously, safety is one of the top concerns when selecting a home. When asked to specify the disadvantages of living in close proximity to a pond, safety is seen as the most significant disadvantage, with 32% of the respondents stating this (Fig. 7). Although the ponds were well established, this result contrasts with previous work, where safety concerns were mostly attributed to newly established pond (Apostolaki *et al.* 2006), and well-established ponds were considered rather more positively by residents. The second most common concern was rodents (21%). However, it is likely that this response represents a fear rather than a real observation, as neither mammals nor reptiles were commonly spotted at any pond location.

Once more, it should be noted that the results presented here are means and that there were significant variations between sites. This point is illustrated in Fig. 8, where it can be seen that, for the Dunline pond, respondents identified safety as one of the most important

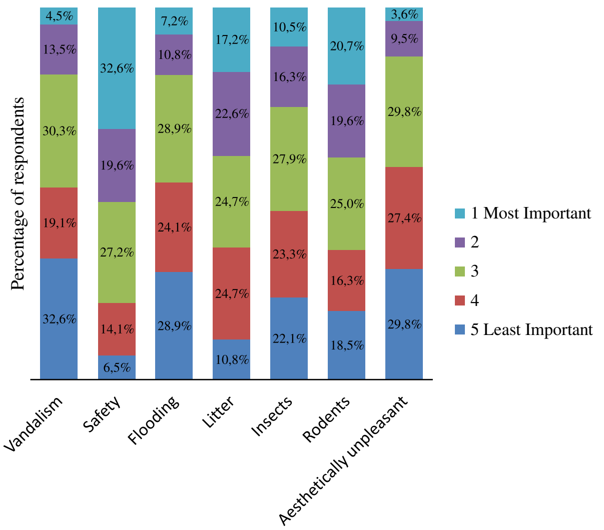

Fig. 7. Perceived disadvantages of living in close proximity to a pond.

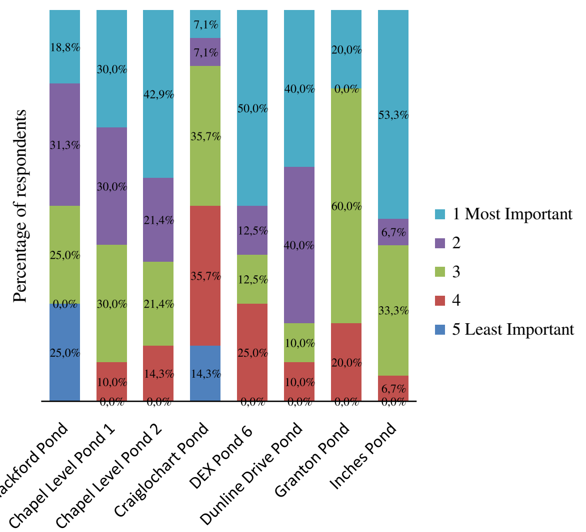

Fig. 8. Safety perception at different pond sites.

concerns. Conversely, safety at the Craiglockart pond achieves a comparatively low score. A further point of note is that the highest safety concerns (above 60%) were associated with ponds designed to Scottish Water standards. In contrast, ponds designed to different standards (privately or council owned) and hence not necessarily providing obvious safety measures are not perceived as particularly dangerous (scores below 50%). This demonstrates that specific safety measures taken by Scottish Water (including barriers, low gradient slope and reed bed protection) may have failed to reduce the hazard level perceived by residents.

The second most significant concern was pollution. However, this was most heavily linked to the aesthetics

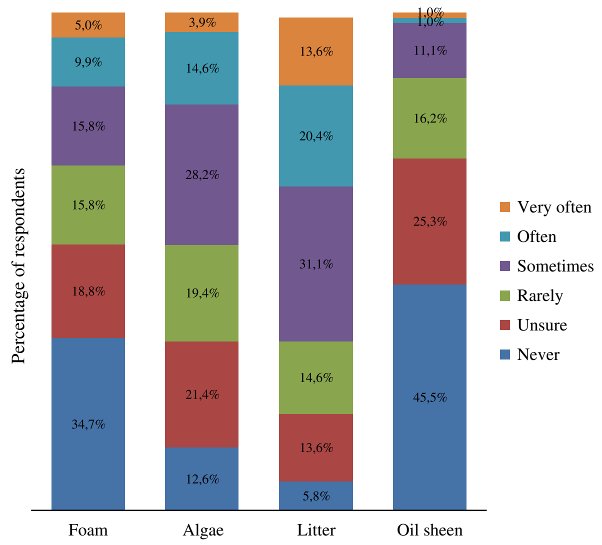

Fig. 9. Observed pollution in close proximity to ponds.

of the pond – the most common form being litter (Fig. 9). Once more, the results varied from one pond to another, with Granton, Craiglockart and Blackford locations achieving the top three cumulative scores (Fig. 10). These scores are highly related to the maintenance perception: when asked whether they thought the ponds were appropriately maintained or not, locations achieving the lowest scores were also Granton, Blackford and Craiglockart, with respective scores of 75, 57 and 47%. A chi-square test with a 5% level of significance reveals that there is a strong correlation between perception of the ponds' need for maintenance and the amount of litter respondents have been able to spot in the pond: the presence of litter clearly affects the perception that residents have of their pond and how it is maintained.

Wildlife

Regarding wildlife spotted by residents, respondents identified birds (small and large) as the most commonly spotted animals, whereas insects, amphibians and mammals occupy the next places. Reptiles, uncommon in Scotland, were seldom spotted by the residents (Fig. 11). The observation of wildlife is largely influenced by the location of the pond and its surroundings. Figure 12 shows that Craiglockart and Blackford ponds were perceived as having the highest wildlife presence, with both locations having over 70% of birds spotted by residents.

Comparison with previous work

Although the presented research was undertaken using a wider range of sites and had a higher number of responses

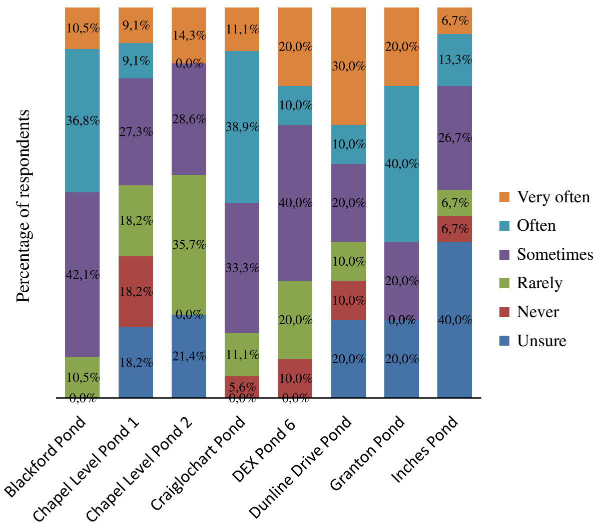

Fig. 10. Litter spotted in close proximity to ponds by location.

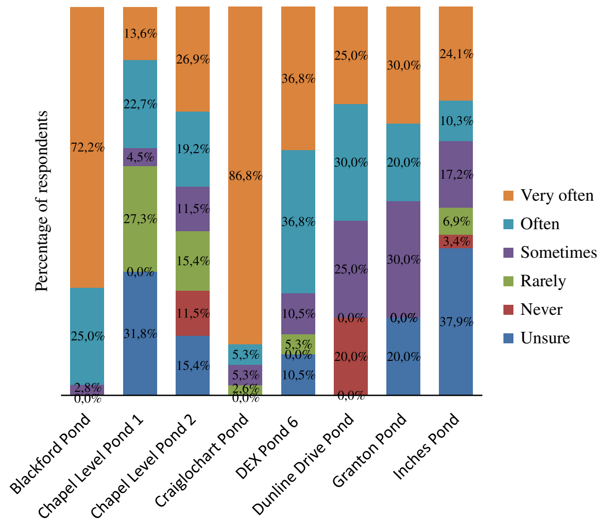

Fig. 12. Large and small birds observed at each pond.

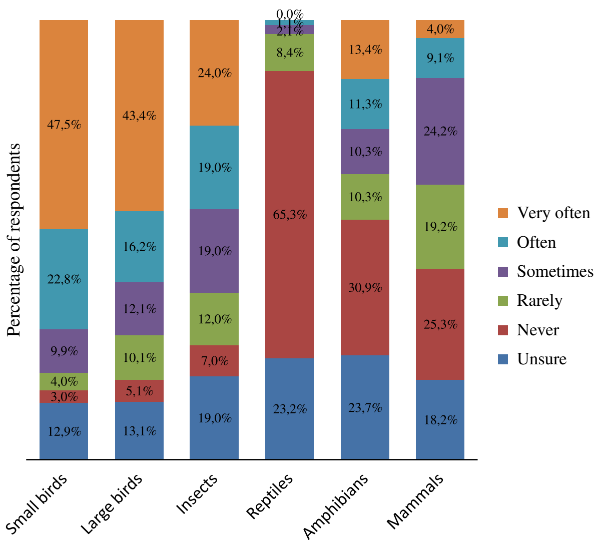

Fig. 11. Types of wildlife spotted.

than that used in other projects, it is possible to make comparisons:

• Apostolaki *et al.* (2006) reported low-level awareness of SuDS systems and their functions, with only 6% of respondents having knowledge of how they are expected to perform. In contrast, the reported research found that 26 and 42% of the respondents claimed they were aware or vaguely aware, respectively, of the pond's function. This finding may reflect increased awareness of environmental issues.

• Some advantages are preponderant on others. For example, the presence of wildlife (largely small and large bird species) is perceived as being a key benefit, followed by drainage performance and amenity. Education, pet walking area and increased property values were perceived as secondary advantages. These results are similar to those obtained by Apostolaki *et al.* (2006), the only substantive difference being increased awareness and appreciation of the drainage function. Again, this may highlight an increased awareness of sustainable development and urban flood risk management.

• There is no substantive change in health and safety perception despite recent efforts to improve safety (CIRIA 2007; Scottish-Water 2007). Residents continue to perceive ponds as a potential hazard. However, this should be placed within the context of the perceived risks associated with other elements of the urban fabric. For example, in 2005, 8.7% (38) of all UK accidental drowning happened in urban areas. Of these, six were in ponds and 25 were in baths. In the same year, there were 1099 deaths and 164 298 injuries on urban roads (ROSPA 2010).

• Litter spotted around ponds remains an issue for residents. This observation places extra emphasis on the need for frequent maintenance to improve the amenity provided by the pond.

Financial

The monetary value associated with the presence of the pond was assessed using the CV methodology based on a recognised methodology (Arrow *et al.* 1993). In the final part of the questionnaire, respondents were asked whether they thought the potential benefits of living in close proximity to the pond could offset the perceived disadvantages. A total of 60% of the respondents answered yes, 26% were unsure and only 14% answered no. A chi-square test with a 5% level of significance was used to confirm the statistical significance of any correlations between this question and the previous questions answered by the respondents. A statistically significant link was found for the following:

- Respondents who have direct visual access to the pond from their lodgings felt that the pond had a positive impact that could offset the potential disadvantages.
- Similarly, there was a significant link between those who valued the wildlife provided by the pond and those who felt that benefits could outweigh disadvantages.
- Conversely, those who felt litter was a problem also felt that benefits could outweigh disadvantages.

Those residents who viewed the pond positively were asked to give an estimate of the monetary value they would be willing to pay monthly to find advantages similar to those offered by the pond in another location. Thus, this question was asking them to associate the perceived benefits associated with the pond with a monetary value. Although a good co-operation rate of 82% for this sensitive question was achieved, the most common answer was £0.00 with 50%. The absence of answer (18%) was interpreted as a refusal to pay and was encoded as £0.00.

The average willingness to pay (Table 3) for the different ponds is very different from one site to another. Privately or council-maintained ponds (Blackford, Craiglockart and Granton) are clearly at the top of the ranking, whereas ponds designed and maintained to Scottish Water standards achieve a lower willingness to pay. With a weighted average willingness to pay of £18.71, privately or council-maintained ponds are clearly outranking Scottish Water-owned ponds, reaching a weighted average willingness to pay of £5.62. This result indicates that the perception of Scottish Water designed ponds is below the perception of other privately or council-maintained ponds. Consequently, despite recent guidelines (CIRIA 2007; Scottish-Water 2007), this result indicates that efforts are still needed to progress the design of Scottish-Water maintained ponds.

For all the locations combined, an average £10.95 per month per dwelling for the residents living in close proximity to ponds has been established. Based on the costing methodology recommended by HM Treasury (2003), the net present value of the average willingness to pay over 50 years is calculated by adjusting future willingness to pay with a discount rate of 3.5% up to 30 years, followed by 3% for the remaining years. The equivalent amount of money corresponds to £3324 per dwelling over a 50-year period and it is thought that residents' contribution could help in offsetting the construction and maintenance costs of ponds, although the way in which money could be collected is not discussed here.

Table 3 Contingent valuation for the different sites

Pond location (sample size)	Average willingness to pay (£/month)
Pond 6 Dex (11)	3.20
Chapel level 2 (15)	3.60
Inches (17)	5.00
Dunline (10)	8.00
Chapel level 1 (11)	9.60
Blackford (19)	15.70
Craiglockart (20)	20.00
Granton (5)	25.00
Weighted average (108)	10.95

To offset the cost of building and maintaining a pond to the amenity provided to those living in close proximity, it is important to consider minimum development densities. As a case in point, assuming a high maintenance level and using published data (Bastien *et al.* 2010a, b) to determine construction and maintenance costs, the net present value of a 2400 m^3 pond capable of draining a 20 ha residential area has been estimated to be around £227k. Assuming that 7 ha of development would have access to the pond in similar conditions to that presented in the survey, a density > 10 dwellings/ha is sufficient to offset the costs of construction and maintenance of the pond over a 50-year period.

Conclusions

While not directly influencing the choice to move into an area, even for well-designed systems, ponds offer advantages that residents have been able to clearly identify. In summary, based on the research presented in this paper, it is possible to draw the following conclusions:

(1) Residents have identified wildlife as the most important benefit, and this impacts on their potential willingness to pay. This finding underlines the need to use treatment trains before runoff is discharged to a pond to manage runoff quantity and quality efficiently, and thus maximise wildlife and amenity potential (Helfield & Diamond 1997).

(2) Confirming the findings of previous studies, health and safety risks were identified as the main concerns of residents. However, these should be seen as site specific and low relative to other urban risks. Despite the relatively low number accidents reported due to drowning in waterbodies relative to other urban hazards, recent guidelines that aim to reduce any threat ponds pose appear to have had a limited impact on the perception of residents. Raising awareness and informing residents on the nature of the risks posed may be the key to gaining greater acceptability of SuDS ponds.

(3) Pond functions are generally well understood and the presence of litter, even if it is felt as a disadvantage, is not an obstacle to residents and does not affect their willingness to pay.

(4) The average potential benefits generated by the amenity provided by the pond could serve to offset construction costs and maintenance of the pond. Application to a case study has shown that even a very low urban density development would achieve sufficient potential monetary benefits to offset the cost and maintenance of the pond over a 50-year period.

Acknowledgement

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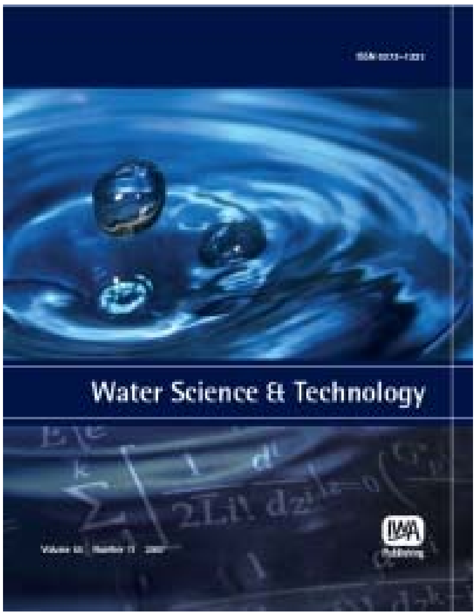
Water Science & Technology

The best management of SuDS treatment trains: a holistic approach

Nicolas Bastien, Scott Arthur, Stephen Wallis and Miklas Scholz

ABSTRACT

The use of Sustainable Drainage Systems (SuDS) or Best Management Practice (BMP) is becoming increasingly common. However, rather than adopting the preferred "treatment train" implementation, many developments opt for end of pipe control ponds. This paper discusses the use of SuDS in series to form treatment trains and compares their potential performance and effectiveness with end of pipe solutions. Land-use, site and catchment characteristics have been used alongside up-to-date guidance, Infoworks CS and MUSIC to determine whole-life-costs, land-take, water quality and water quantity for different SuDS combinations. The results presented show that the use of a treatment train allows approaches differing from the traditional use of single SuDS, either source or "end of pipe", to be proposed to treat and attenuate runoff. The outcome is a more flexible solution where the footprint allocated to SuDS, costs and water quality can be managed differently to satisfy more efficiently the holistically stakeholders' objectives.

Key words | BMP, green roof, permeable paving, pond, runoff quality, SuDS, swale, treatment train

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INTRODUCTION

The use of Sustainable Drainage Systems (SuDS) or Best Management Practice (BMP) has been made compulsory for virtually all new developments in Scotland. However, despite the design guidance (CIRIA 2007), systems are often implemented using "end of pipe" or source controls SuDS rather than an integrated series of SuDS devices–a "treatment train". Indeed, in 2002, over 70% of sites in Scotland were reported as using only a single SuDS component (Wild *et al.* 2002). The management of runoff using a treatment train is preferred by the UK's environmental regulators (SEPA 2006; Environment-Agency 2007) as it provides the following advantages:

- using different and complementary removal techniques can achieve enhanced pollutant removal;
- pollutant spills can be detected and managed in a more efficient manner by making the drainage infrastructure visible;
- an enhanced level of treatment is achieved by treating pollutants closer to their source; and,
- the shock load effect on regional controls is reduced, thus enhancing biodiversity by providing a stable habitat.

Although the benefits of SuDS have been reported for some time, land take, construction costs, uncertainty regarding maintenance and adoption of SuDS are generally seen as barriers to implementation of source and site controls. In contrast, providing a good quality of life by improving environmental amenity and biodiversity in urban areas are key drivers for planners. By considering these views, the underlying philosophy of the presented research is that the development of a surface water management plan at an early stage, coupled with advances in how the treatment train is modelled, would help optimise water management and planning objectives. The aim of the reported study is therefore to evaluate the potential benefits

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of using different treatment train solutions for a case study. Holistic evaluation of the different solutions is undertaken by focusing on four key stakeholder objectives:

- land take;
- whole life costs;
- water quality; and,
- managing flood risk.

The potential benefits achieved by the use of source and site controls are then used to reduce regional treatment facilities size, hence offering the opportunity for developers and planners to manage the footprint differently whilst still satisfying water quality and quantity objectives.

METHODOLOGY

The methodology developed can be divided into three modules:

1. Development of source, site and regional controls scenarios–this module focuses on selecting appropriate source and site controls that can be incorporated within the treatment train.
2. Treatment train assessment–this module aims to provide a novel holistic assessment of the treatment train based on key stakeholder objectives. The assessment of the treatment train aims to evaluate how the main stakeholder objectives are satisfied and is based upon:
    a. Land take: Determination of the land occupied by the SuDS devices is undertaken using recent design guidance (CIRIA 2007; Scottish-Water 2007).
    b. Costs: Whole life costs over a 50 year period.
    c. Water quality: To estimate the pollutant removal capacities of a range of SuDS, first order decay kinetics (Kadlec & Knight 1996) will be used.
    d. Water quantity: Evaluation of the potential for source and site control to attenuate the volume reaching regional control was undertaken.
3. Proposal for regional controls size reduction–this module discusses the possibility of reducing regional control size by objectively incorporating attenuation and water treatment at source and site control level.

Case study

The Clyde Gateway, situated along the River Clyde in Glasgow, is a priority regeneration area for the Scottish Government. Recent flooding in Glasgow, poor watercourse quality and the need to regenerate this neglected area as a "sought after" location led to the development of a forward looking surface water management plan (Auckerman *et al.* 2008). The reported project uses a small part of the Clyde gateway, Dalmarnock Road area (Figure 1), to generate development scenarios. Due to its heavy industrial past, infiltration of water into the soil will be prevented to avoid migration of pollutants into the groundwater. The study area comprises 20 hectares where 1,500 houses will be constructed. If no source or site controls are used, a regional pond of approximately 2,200 m^2 will be required to treat runoff to an acceptable level, and an additional 2,600 m^2 will be required to store runoff up to a 100 year return period storm (2.5% of the catchment area).

Regarding current development plans for the Dalmarnock Road area, the northern extent of the site has been described as a "new destination and gateway" and will benefit from major public investment to develop public transportation (Glasgow City Council 2007). Development density for the site suggests a decreasing density gradient from the north to the south: higher densities towards the city centres and then decreasing progressively towards the suburbs. Although more accurate development plans will be considered in the future, the view adopted in this paper

Figure 1 | The Dalmarnock Road area contained within the Clyde Gateway boundaries.

is that development of SuDS will be dependent on existing pressure on land take due to development density. Adopting this view, it has been considered that the SuDS implemented will depend on the amenity they can provide to the surroundings (Apostolaki & Jefferies 2005):

- The northern part of the site will not see above ground SuDS devices unless they are part of the infrastructure (e.g. green roofs).
- The central part is more likely to adopt SuDS devices where they present a high amenity, thus improving biodiversity and urban well being (e.g. pond).
- The southern part of the site will be a low development site where development of low amenity SuDS is acceptable (e.g. swale).

The diffuse pollution arising from land use activities dispersed across the catchment mainly comprise suspended sediments, polycyclic aromatic hydrocarbons (PAHs), heavy metals, nutrients and phosphates issued from erosion, vehicles, maintenance of green spaces and animal droppings (SEPA 2006; Morgan 2007). However, dissolved particles such as PAHs and heavy metals have an affinity for suspended particulate solids and are bound to them–mainly to the smallest particles (Lee *et al.* 2005). Monitoring of pollutants generated by different land uses (Duncan 1999; Mitchell 2005; Gobel *et al.* 2007) has shown a certain consistency in the amount of pollutants that can be expected for different land uses. Within this context, the estimated pollutant concentrations for total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP) can be found in Table 1. Usually, roads are the main source of suspended solids where they are associated with major pollutants such as PAHs, oil and heavy metals.

Development of source, site and regional controls scenarios

Based on potential land use, site and catchment characteristics, the following seven key SuDS source and site controls have been considered:

(1) Linear wetland (LW) or enhanced swale has been promoted within Glasgow as a method of reducing car use by providing a sustainable and safe green–blue link for pedestrians and cyclists.

Table 1 | Total Suspended Solids, Total Phosphorous and Total Nitrogen vs Land Use (Duncan 1999)

	Residential	Roads	Roofs
TSS ($mg\,l^{-1}$)	160	200	35
TP ($mg\,l^{-1}$)	0.35	0.2	0.15
TN ($mg\,l^{-1}$)	2.63	3	–

(2) Standard conveyance swales (SW) can be used in the southern part of the site where lower density development can be expected, provided infiltration is prevented. Design is following CIRIA's recommendations (CIRIA 2007).

(3) Site ponds (SP) are able to treat pollution from high density developments and if situated in the medium density development area would provide amenity for residents in close proximity. The pond has been designed to capture first flush runoff from the development using recently published guidance (CIRIA 2007; Scottish-Water 2007).

(4) A regional pond (RP) which discharges into the River Clyde is the "default end of pipe" solution in the southern part of the site. Design of the regional pond is also based on recently published guidance (CIRIA 2007; Scottish-Water 2007) and has been designed to capture the first flush for the whole area. The design may include a volume dedicated to attenuate events up to the 100 year return period level.

(5) Green roofs (GR) can be used instead of exposed roofs in the north part of the area were large roof surfaces are more likely to be developed due to increased density.

(6) Concrete Block Pavement (CBP) can be used where traffic speeds are below $60\,km\,h^{-1}$. As such, they can be used in very low density development and on a case-by-case basis in other areas. In this case, their use is applied in the low density development where a pavement distributed across the area will be able to drain rainwater falling on footpaths and roads.

(7) Subsurface storage (SS) can provide storage for attenuation of water runoff anywhere on the area.

Logical combinations of the different SuDS devices allow consideration of twelve different treatment trains comprising one to four SuDS that can be assessed for water quality performance and three SuDS that can be assessed on their ability to attenuate runoff. The impact of using source and site controls will be used to reduce the sizing of regional control.

Treatment train assessment

To apply the methodology, water quality modelling tools will be applied using recent design guidance for the UK and Scotland. As detailed in this section, where pollutant data for the yet to be developed catchment is not available, appropriate surrogate values have been sourced from peer reviewed literature.

MUSIC (model for urban stormwater improvement conceptualisation)

Developed independently of the reported research by eWater Cooperative Research Centre, MUSIC is a hydrological model coupled with a water quality model (Wong *et al.* 2006). Hydrological modelling of SuDS is achieved by representing the elements as a series a well mixed water bodies or Continuously Stirred Tank Reactors (CSTRs)–mimicking potential dispersion. The number of CSTRs (N) used for the different SuDS is linked to the hydraulic efficiency (λ) determined by Persson *et al.* (1998) for a range of structures (Equation (1)). Water quality performance is modelled using first order kinetics (Equation (2)) observed in SuDS monitoring studies (Wong *et al.* 2001; Ackerman & Stein 2008).

$$\lambda = e_v\left(1 - \frac{1}{N}\right) \qquad (1)$$

where:

- e_v: effective volume defined by the proportion of the storage actively engaged by the flow path,

$$q\frac{dC}{dx} = -k(C - C^*) \qquad (2)$$

where:

- q: hydraulic loading rate (m/y)
- x: fraction of distance from inlet to outlet (m)
- C: concentration of the water quality parameter ($mg\,m^{-3}$)
- C^*: background concentration of the water quality parameter ($mg\,m^{-3}$)
- k: decay rate constant (y^{-1})

When using Equation (2), a key consideration is that the hydraulic loading is related directly with the expected discharge per unit area. Thus, the plan area of devices are key factors in the determination of water quality performance (Wu *et al.* 1996). For the SuDS considered in this case study, theoretical calculations derived from sedimentation equations and calibration surveys (e.g. Wong *et al.* 2001) for a range of treatment devices have allowed an array of values for k and C^* to be determined. It should be noted that the calibration of k and C^* relies heavily on particle size distribution. In the absence of such data for the Glasgow area, data from surrogate catchments has been used (Walker & Wong 1999).

Using this approach, the MUSIC model was used to estimate water quality improvements for SuDS where areas of facilities are considered as an important factor in the removal of pollutants (ponds, swales and linear wetland). To estimate water quality benefits of the treatment train for the case study, a one year return period rainfall event of 60 minutes duration (M1-60–corresponding to 12 mm of rainfall) with a suspended solids Event Mean Concentration (EMC) of 160 $mg\,l^{-1}$ (Duncan 1999) has been used as this event and the resultant pollutant concentrations will represent standard conditions for which SuDS have been designed (Figure 2).

SuDS performances, depending on their position in the treatment train are presented in Table 2. It can be seen that the model performance is within the range of reported values, confirming that MUSIC can be used to estimate realistic SuDS performance. As would be expected, the water quality performance of ponds varies with their position in the treatment train–this can be explained by

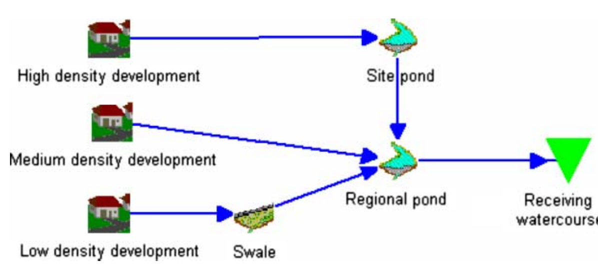

Figure 2 | Example of a SuDS treatment train modelled with MUSIC.

Table 2 | Comparison of removal efficiencies for TSS (as % of mass removed)

	SuDS position in the treatment train and MUSIC performance				
	1st	2nd	3rd	Reported removal efficiency	Reference
SuDS					
Site pond	68	–	–	26–92	e.g. Morgan (2007)
Regional pond	65	57–64	0–50		
Swales	87	–	–	30–98	e.g. Deletic (2005)
Linear wetland	64–66	68–96	–		
Concrete block pavement	80*	–	–	50–95	e.g. Gilbert & Clausen (2006)

*Adopted value based on reported literature.

the fact that high removal efficiencies are more difficult to obtain where pollutant levels are low or the flow has been pre-treated. Conversely, improving water quality performance for the linear wetland can be explained by the capacity of upstream SuDS devices to regulate hydraulic discharge and improve filtration performance within the linear wetland.

Whole life cost estimation

For all the SuDS considered, the costs have been determined based on the construction costs of the devices and associated maintenance over a 50 year period (Table 3). As these systems have been chosen to provide a high amenity to the community and support urban biodiversity, a high level of maintenance has been used to determine the costs. The net present value of costs has been calculated by adjusting future costs with a discount rate of 3.5% up to 30 years, followed by 3% for the remaining years (HM Treasury 2003). Potential economies realised on infrastructure have been calculated and taken into account (i.e. pipe network, asphalt pavement or exposed roof).

Proposition to reduce regional control size

The size of the regional control size, and hence its land take, is a function of the volume allocated to the permanent pool and the attenuation storage. The volume allocated to the permanent pool and the attenuation has initially been driven by the need to capture the first flush and the required attenuation storage of runoff to limit impacts of increased peak flows on downstream watercourses (Roesner *et al.* 2001). Consequently, reduced land take can either be achieved by providing attenuation at source and regional control level, or by taking into account the treatment provided upstream (usually not taken into account unless it is designed on the basis of treatment volume) by source and site controls as described below:

Reduction of treatment volume

A pond's performance is largely driven by pond surface area (Wu *et al.* 1996). Consequently, reducing the pond's surface area will reduce pollutant removal efficiency by increasing the hydraulic loading. Using the water quality model, the estimation of water quality performance is achieved using the hydraulic and water quality models described previously, thus giving the opportunity to move away from the traditional capture of the treatment volume used in the UK to design SuDS.

Reduction of attenuation storage

Regarding water quantity benefits, the extent to which the water should be stored in the catchment before discharge is decided in consultation with the environmental regulator (regarding the protection of watercourse for environmental reasons) and with the local authority (as part of their flood prevention duties). Attenuation at source and site control levels will allow a reduction in the volume dedicated to attenuation at the regional control level.

Table 3 | Maintenance activities for the SuDS considered

SuDS maintenance costs (sources)	Routine maintenance	Infrequent and corrective maintenance
Green roofs (turfs) (Wong *et al.* 2003)	Barrier vegetation pruning, weeding and management	Vegetation replacement
	Drainage inspection	
Regional and site ponds (UKWIR 2005)	Inspection and reporting	Sediment removal
	Litter and minor debris removal	Vegetation replacement
	Grass cutting	
	Barrier vegetation pruning, weeding and management	
Swales and linear wetland (UKWIR 2005)	Inspection and reporting	Sediment removal
	Litter and minor debris removal	Vegetation replacement
	Grass cutting	
Subsurface storage (Duffy *et al.* 2008)	Inspection and reporting	Blockages–Jetting
	Litter and minor debris removal	Repair broken components
	Grass cutting	
Concrete block pavement (UKWIR 2005)	Desilt inlets and outlets	Relocation of block paving
	Jetting	Replacement of jointing and laying material
	Repair broken components	Mechanical cleaning
Infrastructure maintenance costs	**Routine maintenance**	**Infrequent and corrective maintenance**
Asphalt pavement (Interpave 2006)	Surface course repairs	Surface dressing
		Excavation and reinstatement
		Cleaning of drainage facilities
Pipe network (Langdon 2009)	–	–
Exposed roofs (Wong *et al.* 2003)	Drainage inspection	Roof membrane replacement

RESULTS AND DISCUSSION

Using the novel methodology presented in the previous section, assessment of the different treatment trains was undertaken. The results of this analysis are presented in this section along with proposals for a framework whereby the size of regional ponds may be reduced based on the water quality and quantity benefits of using source and site controls.

As illustrated in Figure 3, by using SuDS in series, significant benefits in terms of water quality improvements can be achieved. From a basic removal of 65% of TSS for a single regional pond, the removal efficiency can reach 95% when several SuDS are used in series. Removal rates for TP and TN vary accordingly. By increasing the removal of TSS, the removal of small particles is improved, thus improving the treatment for heavy metals and PAHs–these pollutants are more likely to be bound to the small fraction of TSS (Lee *et al.* 2005).

Estimation of the costs associated with the different treatment trains (Figure 4) shows that using multiple SuDS source and site controls has a significant cost impact. However, it should be noted that the implementation of swales in the low density area does not add a significant cost to the project as their construction can partly be offset by economies on infrastructure costs (Astebol *et al.* 2002). For this case study, the cost of implementing SuDS for water quality treatment can increase by up to a factor of 5 compared to the end of pipe pond. Notwithstanding this, Figures 4 and 5 show that, in some scenarios, significant increases in water quality performance may be obtained for only a modest additional cost (e.g. the use of a regional pond and a linear wetland).

A further point to note is that unless SuDS are part of the infrastructure (e.g. CBP), they can add significant land take to that of the initial regional control (Figure 5). In this case, the land take associated with the use of source and site

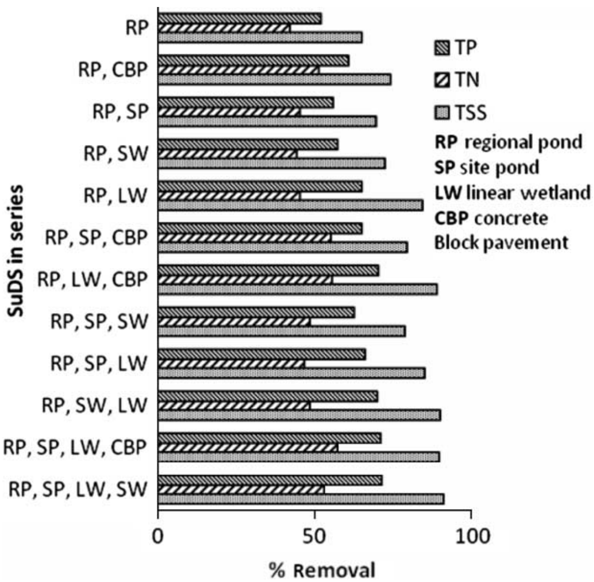

Figure 3 | Different SuDS solutions and their modelled TSS, TP and TN removal capabilities.

controls can multiply up to seven times the land take of the regional control pond.

Reviewing Figures 3–5, it can be seen that significant water quality benefits can be achieved using a SuDS treatment train. However, in many cases, these improved benefits must be seen within the context of increased land take and/or construction costs in most of the cases.

Proposition to reduce regional control size

Regional control size can be reduced by two different means:

- Reduction of the treatment volume by taking into account benefits of source and site controls.
- Reduction of the attenuation volume by providing attenuation at source and site control levels.

Reduction of the permanent pool

Considering that 65% suspended solids removal is adequate and if the treatment train produces a level of treatment beyond that level then the regional pond may be reduced in size until the target performance is reached.

Using the results summarised in Figures 3–5 and Table 2, it is possible to consider reducing the size of the regional pond. The rational for doing this is based on the current practice in the UK–end of pipe ponds provide an acceptable level of treatment (shown to be 65% TSS removal in analysis presented in Table 2). In doing this it should be noted that although the reduction of TSS achieved by upstream SuDS devices gives a good indication of how SuDS are performing, the dissolved solids performance, including most TN and TP, is significantly reduced in this case as the treatment train does not provide any permanent pool where biochemical degradation of dissolved particles is achieved. As illustrated in Table 4, in most cases, the reduction in land take of the regional control does not compensate for the land used by upstream source and site controls unless these are part of the infrastructure (e.g. CBP). Although this may be viewed as a disadvantage, it may be considered by the developer as an alternative way to spatially manage the SuDS footprint. An example of this is the land take associated with swales: their position along the roads may make them more acceptable than setting aside a large area for a regional pond.

Reduction of the attenuation volume

The attenuation of the runoff volume can be undertaken at source and site control levels. The land take associated with

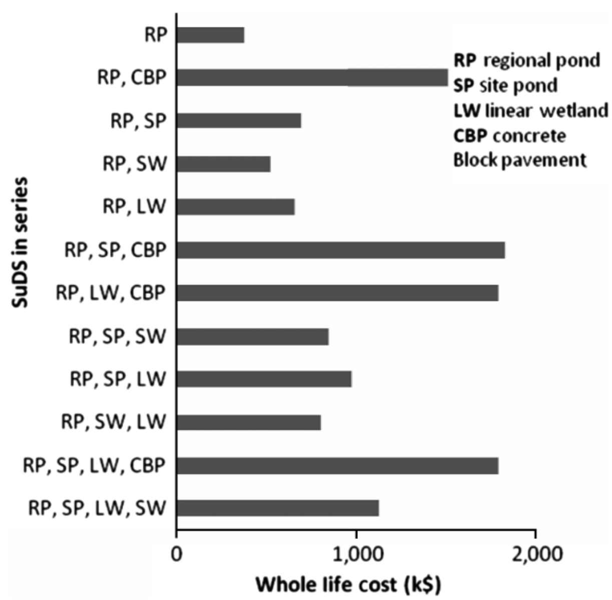

Figure 4 | Whole life cost estimates for a range of treatment trains.

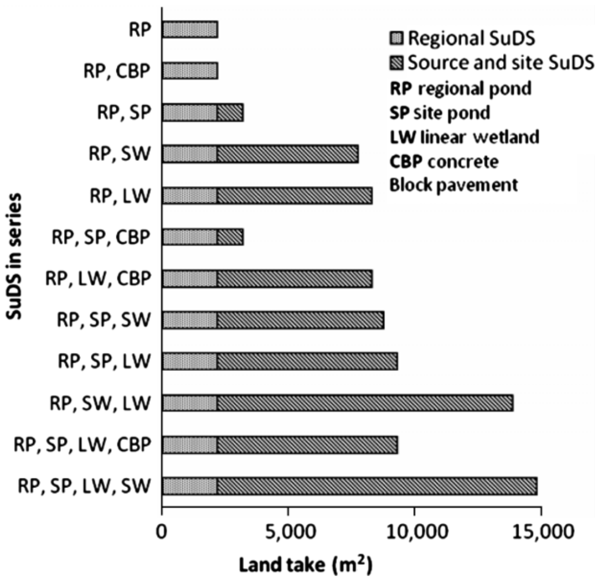

Figure 5 | Land take for different treatment trains.

the storage of the 1, 30 and 100 year return period events in addition to the land take of the permanent pool is respectively of 3,529, 4,363 and 4,788 m^2 for respective volumes of 2,616, 5,560 and 7,220 m^3. Reduction of volumes reaching the regional control through the use of source and site control will help reduce land occupied by the regional control. Within this context, the SuDS can either be designed as specific attenuation devices or to simply slow the runoff.

Regarding SuDS slowing the runoff:

- Swales and linear wetlands: Infoworks simulations have indicated that equivalent reduction achieved is less than 15% for the linear wetland and less than 0.5% for the swales for 100 year return events. There will be no additional costs as these SuDS have been designed previously for water quality.

Regarding SuDS designed specifically for attenuation:

- Site and regional ponds: retention of water can take place either at the regional pond level to attenuate runoff for the whole area or at the site pond level to attenuate high density development runoff following Scottish-Water (2007) recommendations.
- Subsurface storage can store the designed volume and impacts only on costs (Duffy *et al.* 2008).
- Green roofs: Literature on the performance achieved by green roofs in terms of attenuation reports a wide range of values depending mostly dependant on the depth of substrate (CIRIA 2007). Deutsch *et al.* (2007) recommend designing for the green roof retaining the first 25 mm for each rainfall event. This value together with the costs

Table 4 | Achievable reduction in land take based on TSS removal with RP (Retention Pond), SP (Site Pond), LW (Linear Wetland), SW (Swales) and CBP (Concrete Block Pavement)

		Achievable reduction of regional SuDS land take based on TSS removal		Achievable reduction of SuDS treatment train's land take based on TSS removal	
SuDS treatment trains	Initial treatment train land take (m^2)	(m^2)	(%)	(m^2)	(%)
RP, SP, LW, SW	14,824	0	100	12,624	15
RP, SP, LW, CBP	9,300	0	100	7,100	24
RP, SW, LW	13,824	0	100	11,624	16
RP, SP, LW	9,300	0	100	7,100	24
RP, SP, SW	8,724	850	61	7,374	15
RP, LW, CBP	8,300	0	100	6,100	27
RP, SP, CBP	3,200	850	61	1,850	42
RP, LW	8,300	850	61	6,950	16
RP, SW	7,724	1,600	27	7,124	8
RP, SP	3,200	1,600	27	2,600	19
RP, CBP	2,200	1,600	27	1,600	27
RP	2,200	2,200	0	2,200	0

determined by Wong *et al.* (2003) for the development of an extensive green roof and taking into account potential economies realised on the construction of conventional roof lead to the development of Equation (4). The relationship suggests that, although the runoff volumes considered are modest, green roofs will be beneficial in the longer term. This view, supported by several authors (Acks 2006; Carter & Andrew 2008), is based on the theoretical assumption that the choice of a low maintenance vegetation associated with an extended lifespan can offset the construction and maintenance of an exposed roof. The longer term benefits may be reinforced by evaluating the extent to which green roofs provide better insulation and reduce heating and cooling costs as a result (Wong *et al.* 2003; Carter & Andrew 2008). The use of intensive green roofs, presenting a higher amenity, would achieve better attenuation at a greater cost and will not be investigated here.

The whole life costs as a function of the stored volume that can be stored have been estimated for each SuDS device (Equations (3–5) for ponds, sub-surface storage and green roofs respectively). The associated whole life costs for each SuDS have been calculated either as an additional cost for SuDS initially designed for water quality (e.g. pond) or as a supplementary cost for SuDS only designed for water attenuation (subsurface storage and green roofs) and taking into account potential economies realised on infrastructure (use of exposed roofs).

$$\mathrm{WLC_P} = 19.31 \times V + 43{,}309 \tag{3}$$

$$\mathrm{WLC_{SS}} = 220.7 \times V + 13{,}259 \tag{4}$$

$$\mathrm{WLC_{GR}} = -710.3 \times V + 20.5; \quad V_{\max} = 650 \tag{5}$$

with:

- WLC: Whole Life costs (US$)
- V: Stored volume (m^3); $V_{\max}$: Maximum volume stored

In summary, the use of swales and linear wetland can be considered as cost efficient considering these are providing water quality benefits but benefits in terms of water quantity cannot be considered as a good solution where attenuation of high return periods is required. The use of green roofs appears to be the most cost effective solution to store runoff, but they offer only a limited storage volume. Thus, integrating the attenuation storage within the existing retention pond is the most cost effective solution to store high return period events when compared to traditional subsurface storage. However, where land take is an issue, subsurface storage will remain attractive.

Overall, the choice of SuDS devices to attenuate runoff will depend on the design return period. Low return period events can be attenuated using source and site controls designed to store frequent rainfall events whereas attenuation of high return period (>30 years) will need dedicated structures adding either land take or costs to the project.

CONCLUSIONS

Based on the conclusions presented at the end of the water quality and attenuation sections of this paper, it can be concluded that a novel methodology has been presented which offers an opportunity for the key stakeholders involved in the drainage of surface runoff in urban areas to maximize the benefits of using SuDS in a treatment train. The reduction in regional land take can be achieved based on water quality performance or source and site control attenuation. Despite the problems associated with offsetting regional land take with source and site controls, it has been shown that a different footprint for SuDS can be achieved by using SuDS in series rather than as an end of pipe control. The results obtained should be seen in the context of several SuDS related considerations which will vary greatly between catchments:

- land value in urban areas;
- increased amenity and biodiversity in urban areas;
- better management of accidental pollution; and
- improved degradation of pollutants.

Further work will comprise investigating the potential value of SuDS source and site controls from the point of view of people living in close proximity. This will enable the definition of preferred treatment trains for urban areas depending on land use, catchment characteristics and stakeholders objectives.

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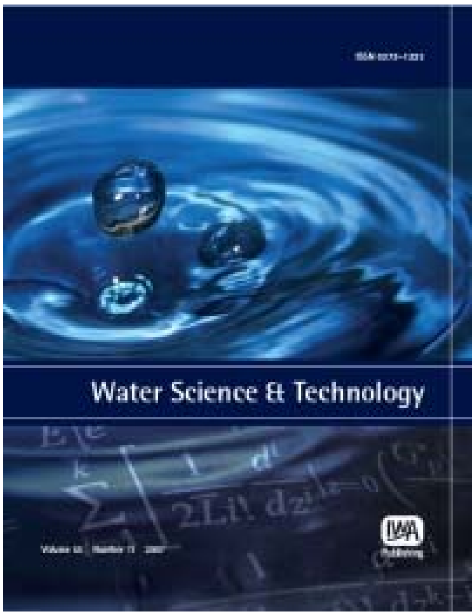
Water Science & Technology

Runoff infiltration, a desktop case study

N. R. P. Bastien, S. Arthur, S. G. Wallis and M. Scholz

ABSTRACT

The use of sustainable drainage systems (SuDS) or best management practice is becoming increasingly common. However, rather than adopting the preferred 'treatment train' implementation, many developments opt for end-of-pipe control ponds. This paper discusses the use of SuDS in series to form treatment trains and compares their potential performance and effectiveness with end-of-pipe solutions. Land-use, site and catchment characteristics have been used alongside up-to-date guidance, Infoworks CS and MUSIC to determine whole-life-costs, land-take, water quality and quantity for different SuDS combinations. The results presented show that the use of a treatment train allows approaches differing from the traditional use of single SuDS, either source or 'end-of-pipe', to be proposed to treat and attenuate runoff. The outcome is a more flexible solution where the footprint allocated to SuDS, costs and water quality can be managed differently to fully meet stakeholder objectives.

Key words | BMP, runoff quality, SuDS, treatment train

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INTRODUCTION

The use of sustainable drainage systems (SuDS) or best management practice has been made compulsory for virtually all new developments in Scotland. However, despite the design guidance (CIRIA 2007), systems are often implemented using 'end-of-pipe' or source controls SuDS rather than an integrated series of SuDS devices – a 'treatment train'. Indeed, in 2002, over 70% of sites in Scotland were reported as using only a single SuDS component (Wild *et al.* 2002). The management of runoff using a treatment train is preferred by the UK's environmental regulators as it provides the following advantages:

- using different and complementary removal techniques can achieve enhanced pollutant removal;
- pollutant spills can be detected and managed in a more efficient manner by making the drainage infrastructure visible;
- an enhanced level of treatment is achieved by treating pollutants closer to their source; and
- the shock load effect on regional controls is reduced, thus enhancing biodiversity by providing a stable habitat.

Although the benefits of SuDS have been reported for some time, land take, construction costs, uncertainty regarding maintenance and adoption of SuDS are generally seen as barriers to implementation of source and site controls. In contrast, providing a good quality of life by improving environmental amenity and biodiversity in urban areas are key drivers for planners. By considering these views, the underlying philosophy of the presented research is that the development of a surface water management plan at an early stage, coupled with advances in how the treatment train is modelled, would help deliver water management and planning objectives. The aim of the reported study is therefore to evaluate the potential benefits of using different treatment train solutions for a case study. Holistic evaluation of the different solutions is undertaken by focusing on four key stakeholder objectives:

- minimise land take;
- minimise whole life costs (WLCs);
- managing flood risk; and
- water quality.

The potential benefits achieved by the use of source and site controls are then used to reduce regional treatment facilities size, thereby offering the opportunity for developers and planners to manage the footprint differently whilst still satisfying water quality and quantity objectives.

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METHODOLOGY

The methodology developed can be divided into three modules:

1. Development of source, site and regional controls scenarios – this module focuses on selecting appropriate source and site controls that can be incorporated within the treatment train.
2. Treatment train assessment – this module aims to provide a novel holistic assessment of the treatment train based on key stakeholder objectives. The assessment of the treatment train aims to evaluate how the main stakeholder objectives are satisfied and is based upon:
   (a) Land take: determination of the land occupied by the SuDS devices is undertaken using recent design guidance (CIRIA 2007; Scottish-Water 2007).
   (b) Costs: WLCs over a 50 year period (HM Treasury 2003).
   (c) Water quality: to estimate the pollutant removal capacities of a range of SuDS, first order decay kinetics (Kadlec & Knight 1996) will be used.
   (d) Water quantity: evaluation of the potential for source and site control to attenuate the volume reaching regional control was undertaken.
3. Proposal for regional controls size reduction – this module discusses the possibility of reducing regional control size by objectively incorporating attenuation at source and site control level.

Case study

The Clyde Gateway, situated along the River Clyde in Glasgow, is a priority regeneration area for the Scottish Government. Recent flooding in Glasgow, poor watercourse quality and the need to regenerate this neglected area as a 'sought after' location led to the development of a forward looking surface water management plan (Aukerman *et al.* 2008). The reported project uses a small part of the Clyde gateway, Dalmarnock Road area (Figure 1), to generate development scenarios. The study area comprises 20 hectares where 1,500 houses will be constructed. If no source or site controls are used, a regional pond of approximately 2,200 m^2 will be required to treat runoff to an acceptable level, and an additional 2,600 m^2 will be required to store runoff up to a 100 year return period storm (2.5% of the catchment area).

Development scenarios were investigated based on the assumption that infiltration of runoff would not be permitted due to the fact that that the site was heavily industrialised in the past years and the soil may be contaminated as a result (Bastien *et al.* 2010). Preventing runoff infiltration would prevent migration of pollutants due to past activities. However, it was agreed that further soil investigations would have to be conducted for the environmental regulator to decide whether the infiltration should be prevented, discouraged or encouraged. In the absence of pollution into the soil, there would be no other barriers apart from those imposed by the land use and associated building regulations to prevent infiltration. Thus, this paper makes the assumption that infiltration will be encouraged in medium and low density areas.

Figure 1 | The Dalmarnock Road area contained within the Clyde Gateway boundaries.

The infiltration rate of the underlying soil is a key parameter in the design of infiltrating SuDS devices. However, in the absence of a survey reporting on the actual infiltration capacities for the site, a desk-based value for the infiltration has been adopted. The geology for the site has been reported as a sand and alluvium mix. CIRIA (2007) reports infiltration rates can vary between 0.5 and 100 m h^{-1} for this type geology and that this range allows a wide range of potential SuDS options to be considered. However, for practicalities, an infiltration rate of 30 m h^{-1} is assumed for an early design solution until further investigations on pollutants containment and possible infiltration rate are undertaken.

Regarding current development plans for the Dalmarnock Road area, the northern extent of the site has been described as a 'new destination and gateway' and will benefit from major public investment to develop public transportation (Glasgow City Council 2007). Development density for the site suggests a decreasing density gradient from the north to the south: higher densities towards the city centre and then decreasing progressively towards the suburbs. Although more accurate development plans will be considered in the future, the view adopted in this paper is that development of SuDS will be dependent on existing pressure on land take due to development density:

- The northern part of the site will not see above ground SuDS devices unless they are part of the infrastructure (e.g. green roofs (GRs)). Infiltration devices will be prevented to cope with building regulations recommending no infiltrate within 5 m of buildings.
- The central part is more likely to adopt SuDS devices where they present a relatively low land take (e.g. infiltration trenches (ITs)).
- The southern part of the site will be a low development area where development of low amenity and relatively high land take SuDS is acceptable (e.g. swale).

Selection of potential SuDS techniques

Based on potential land use, site and catchment characteristics, the following seven key SuDS source, site and regional controls have been considered:

(1) Standard conveyance swales (SW) can be used in the southern part of the site where lower density development can be expected. Design follows CIRIA's recommendations (CIRIA 2007).
(2) Retention pond (RP) discharges into the River Clyde is the 'default end-of-pipe' solution in the southern part of the site. Design of the regional pond is based on recently published guidance (CIRIA 2007; Scottish-Water 2007). The design may include a volume dedicated to attenuate events up to the 100 year return period level.
(3) GRs can be used instead of exposed roofs in the north part of the development area where large roof surfaces are more likely to be considered due to the higher density.
(4) Concrete block pavement (CBP) can be used where traffic speeds are below 60 km h^{-1}. As such, they can be used in very low density development and on a case-by-case basis in other areas. In this case, their use is applied in the low density development where a pavement distributed across the area will be able to drain water from pavements.
(5) Soakaways (SO) can be used in low density development to infiltrate roof runoff.
(6) ITs can be used in the medium density area to drain roads pavement.
(7) Subsurface storage (SS) can provide storage for attenuation of water runoff anywhere on the area.

Logical combinations of the different SuDS devices allow consideration of 19 different treatment trains comprising one to five SuDS which can be assessed to understand the impact of using source and site controls to reduce the size of regional controls. The typical locations of these devices is illustrated in Figure 2.

Treatment train assessment

Water quality, costs, land take will be assessed with the methodology previously developed in Bastien *et al.* (2010) and using hydrological modelling (Infoworks CS), water quality modelling (MUSIC) and up to date guidance in Scotland. The hydrological model will be tested for limited attenuation (30 years return period) and robust attenuation (100 years return period), whereas water quality models performances will be compared using a M1-60 event corresponding to 12 mm of runoff.

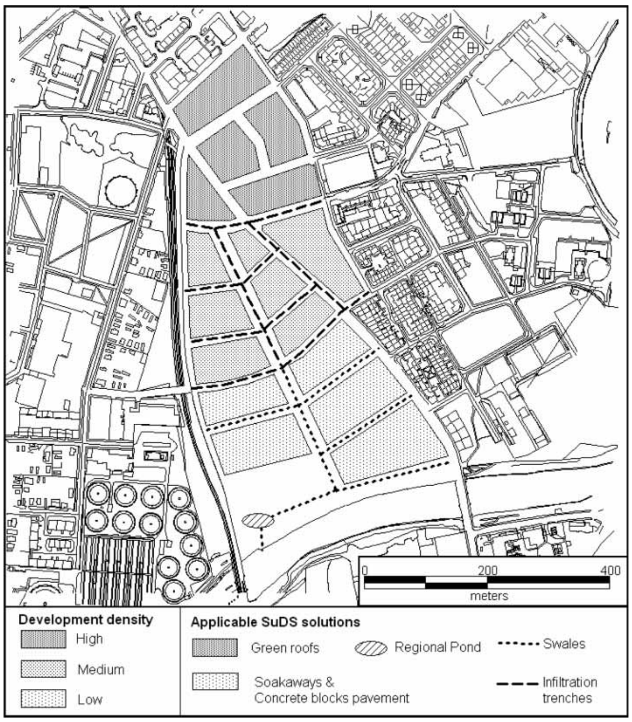

Figure 2 | SuDS deployment for the Dalmarnock Road area.

RESULTS AND DISCUSSION

Preliminary results

Based on the data determined for each SuDS device, assessment of the different treatment trains on the aspects of water quality, land take and costs can be found in Figure 3.

Although the improvement in water quality is desirable, the WLCs associated with the different treatment trains show that using multiple SuDS source and site controls has a significant cost impact and, in this case, can increase the cost of the initial project by a factor of 4. However, it should be noted that the implementation of GRs appears to be financially beneficial in the long term. This view, supported by several authors (Acks 2006; Carter & Andrew 2008), is based on the theoretical assumption that the choice of a low maintenance vegetation associated with an extended lifespan can offset the construction and maintenance of an exposed roof. The longer-term benefits may be reinforced by evaluating the extent to which GRs provide better insulation and reduce heating and cooling costs as a result (Wong *et al.* 2003; Carter & Andrew 2008). Similarly, the implementation of swales in the low density area does not add a significant cost to the project. A further point to note is that unless SuDS are part of the infrastructure (e.g. CBP or GRs), they add significant land take to that of the initial regional control. The attenuation of different return periods also adds significant land take despite the opportunity to size some source and site SuDS to attenuate up to a 30 year period.

Overall, this section confirms the main stakeholder fears (e.g. WLCs and land take) about using SuDS treatment trains rather than using only a single regional SuDS. Indeed, this initial analysis has shown that despite an estimated improved treatment of up to 31, 41 and 49% for respectively total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN), some treatment trains add significant land take and/or costs to the project.

Reduction of regional control size

In new developments there is often pressure to reduce the size of a regional pond. Considering this, a reduction of land take can be achieved based on the use of source and site controls. Regional control size can be reduced by two different means:

- Reduction of the treatment volume by taking into account benefits of source and site controls.
- Reduction of the attenuation volume by providing attenuation at source and site control levels.

Reduction of the treatment volume

Pond performance is largely driven by pond surface area (Wu *et al.* 1996). Consequently, reducing pond surface area will reduce pollutant removal by increasing the hydraulic loading. As shown previously, the use of a single pond, achieves 68% removal of suspended solids. Considering this removal adequate, then if the treatment train produces a level of treatment beyond that level, it follows that the regional pond may be reduced in size until the target performance is reached. Table 1 provides land take of source, site and regional controls achieving at least a reduction of 68% of total suspended solids. For some treatment trains, the regional control appears to be unnecessary, from a water quality perspective, because the upstream treatment train achieves removal of suspended solids beyond 68%. However, this solution may not be acceptable as the pond is the last control before the runoff is discharged and could be considered as security in case source and site controls do not perform to the required standards.

Reduction of the attenuation volume

The attenuation of the runoff volume can be undertaken at source and site control levels. The land take associated with the storage of the 1, 30 and 100 year return period events in addition to the land take of the permanent pool is 3,529, 4,363 and 4,788 m^2 for respective volumes of 2,616, 5,560 and 7,220 m^3. Reduction in the runoff volumes reaching the regional control through the use of source and site control will help reduce land occupied by the regional control.

As shown in Table 1, the use of attenuation and infiltration source devices has a relatively poor impact on the overall land take. This is mainly due to two main reasons:

- The land take of source devices does not offset the land take reduction of the regional control (e.g. swales).
- Infrastructure SuDS, mainly GRs and CBP have a limited impact due to the restrained area where they apply.

To further solve the land take issue linked to the attenuation of the different return periods, the use of hard engineering solutions (i.e. the use of SS) is considered for the area despite possible reluctance on the part of the environmental regulator. SS can store the designed volume and impacts only on costs following Equation (1) (Duffy *et al.* 2008):

$$WLC_{SS} = 220.7 \times V + 13,259 \quad (1)$$

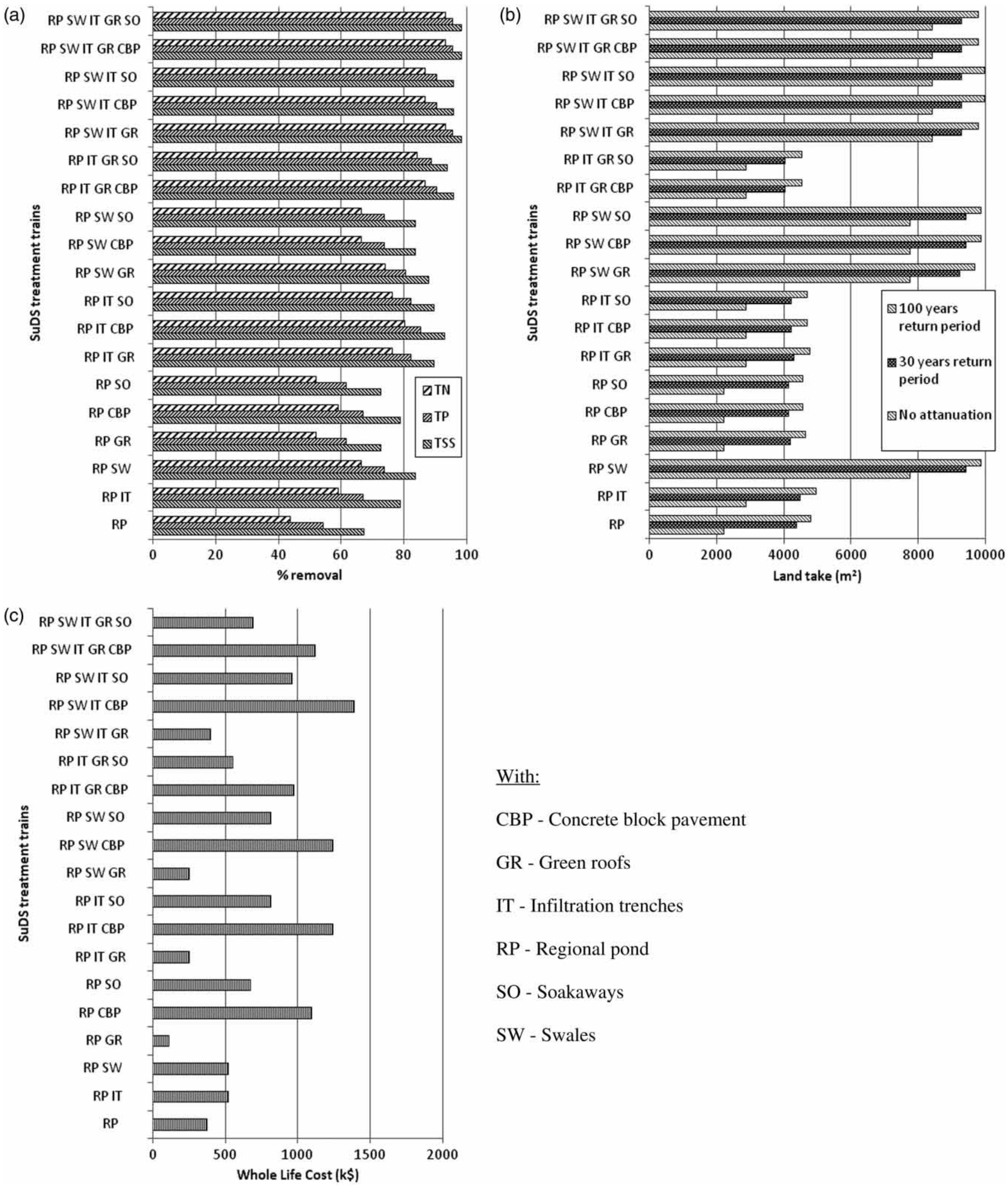

Figure 3 | (a) Water quality estimation for the different SuDS treatment trains. (b) Land take estimation for the different SuDS treatment trains. (c) Whole life cost estimation for the different SuDS treatment trains.

With:

- WLC: whole life costs (US$);
- V: Stored volume (m^3).

Overall, the choice of SuDS devices to attenuate runoff will depend on the design return period. Low return period events (<30 years) can be attenuated using source and site controls – increasing costs and/or overall land take. Attenuation of high return period (>30 years) will need dedicated structures and will be achieved at the regional control site or locally using hard engineering solutions (reducing the footprint but increasing the costs) as shown in Table 2.

Table 1 | Achievable reduction of land take based on suspended solids removal of source and site controls

SuDS treatment trains (with CBP; GRs; ITs; RP regional pond; SW Swales; WB Water Butts; SO)	Initial treatment train land take (m^2)	Achievable reduction of regional SuDS land take (m^2)	Achievable reduction of regional SuDS land take (%)	Achievable reduction of SuDS treatment train's land take (%)
RP	2,200	0	0	0
RP IT	2,871	1,400	64	49
RP SW	7,724	1,400	64	18
RP GR	2,200	300	14	14
RP CBP	2,200	1,400	64	64
RP SO	2,200	300	14	14
RP IT GR	2,871	1,400	64	49
RP IT CBP	2,871	1,800	82	63
RP IT SO	2,871	1,400	64	49
RP SW GR	7,724	1,200	55	16
RP SW CBP	7,724	1,000	45	13
RP SW SO	7,724	1,000	45	13
RP IT GR CBP	2,871	2,200	100	77
RP IT GR SO	2,871	1,600	73	56
RP SW IT GR	8,395	2,200	100	26
RP SW IT CBP	8,395	2,200	100	26
RP SW IT SO	8,395	2,200	100	26
RP SW IT GR CBP	8,395	2,200	100	26
RP SW IT GR SO	8,395	2,200	100	26

Table 2 | Footprint of regional and SuDS treatment trains

	30 years return period attenuation		100 years return period attenuation	
SuDS treatment trains (with: CBP; GRs; ITs; RP Regional pond; SW Swales; WB Water Butts; SO)	Regional control land take (m^2)	Total land take (m^2)	Regional control land take (m^2)	Total land take (m^2)
RP	4,363	4,363	4,788	4,788
RP IT	3,810	4,481	4,270	4,941
RP SW	3,865	9,389	4,328	9,852
RP GR	4,179	4,179	4,621	4,621
RP CBP	4,122	4,122	4,562	4,562
RP SO	4,122	4,122	4,562	4,562
RP IT GR	3,614	4,285	4,088	4,759
RP IT CBP	3,539	4,210	4,020	4,691
RP IT SO	3,539	4,210	4,020	4,691
RP SW GR	3,679	9,203	4,144	9,668
RP SW CBP	3,865	9,389	4,328	9,852
RP SW SO	3,865	9,389	4,328	9,852
RP IT GR CBP	3,350	4,021	3,842	4,513
RP IT GR SO	3,350	4,021	3,842	4,513
RP SW IT GR	3,063	9,258	3,582	9,777
RP SW IT CBP	3,073	9,268	3,766	9,961
RP SW IT SO	3,073	9,268	3,766	9,961
RP SW IT GR CBP	3,063	9,258	3,582	9,777
RP SW IT GR SO	3,063	9,258	3,582	9,777

Cost, land take and flood risk management performance relationships

Based on the results outlined thus far, it is possible to consider how different attenuation and water quality improvement levels impact on both cost and land take. This is best undertaken by considering three design scenarios:

1. Where the design is for water quality improvement only.
2. Where the design is for water quality improvement and limited retention.
3. Where the design is for water quality improvement and robust retention.

Data for these three scenarios are presented in Figure 4 where relationship between land take, costs, water quality and water quantity can be identified.

These plots can serve as a basis for discussion between all the stakeholders involved in the drainage of the Dalmarnock Road area. More specifically, the following consideration can help decision makers to further implement SuDS on the area:

1. The costs appear to be mainly driven by the use of sub-surface storage and CBP in addition to the use of a regional control pond. Whereas land take is driven by the use of regional ponds and swales. Where land take and costs are concerned, GRs and SO have a relatively limited impact in comparison to the use of other SuDS.
2. Considering the Figure 4(a), it can be seen that by using a treatment train, significant water quality improvements

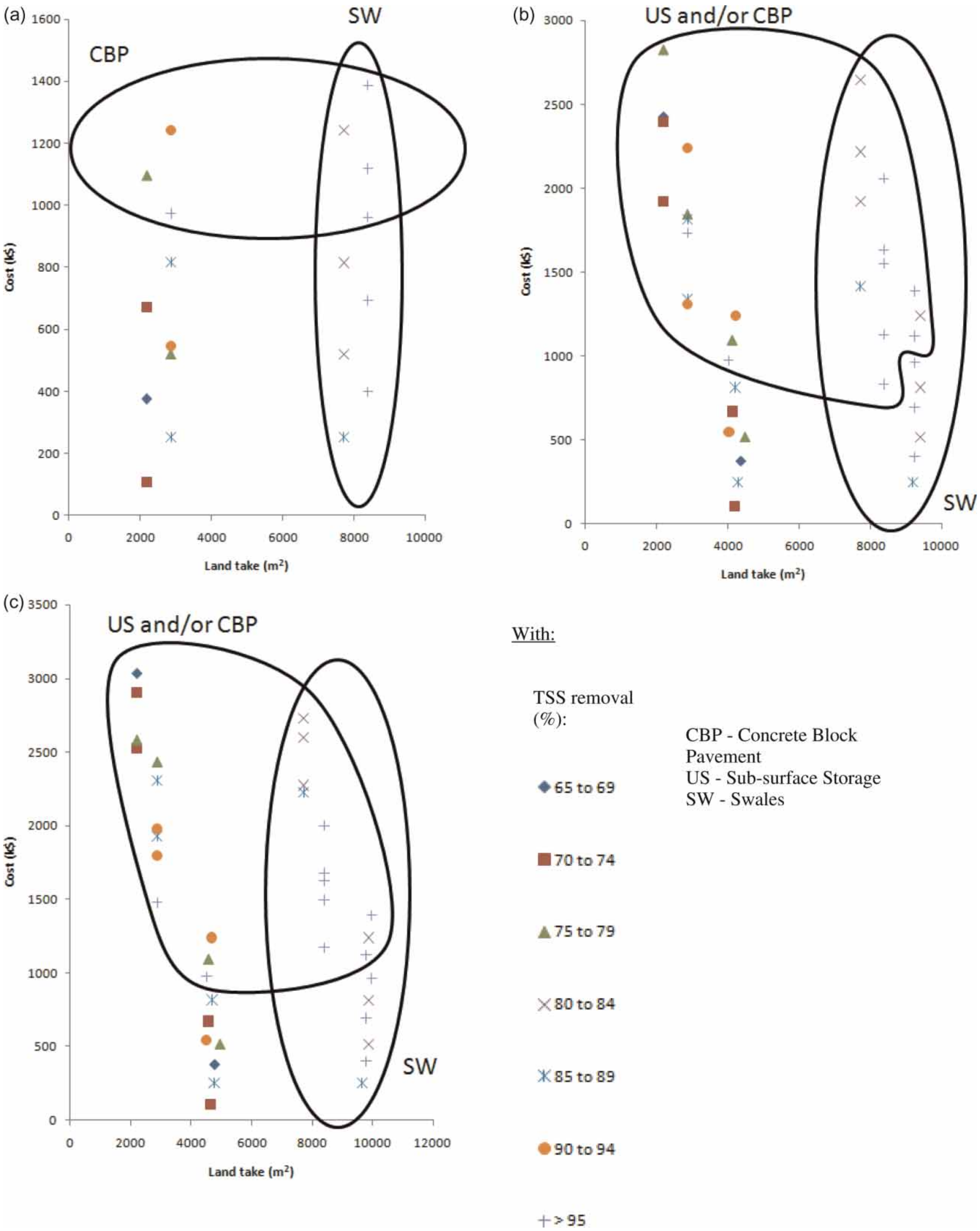

Figure 4 | (a) Cost size attenuation relationship when no attenuation is required. (b) Cost size attenuation relationship with 30 years attenuation. (c) Costs size attenuation relationship with 100 years attenuation.

can be obtained compared to the initial solution of using an end-of-pipe pond: the initial removal rate, below 70% for TSS can be improved beyond 95% by either implementing a swale network or by using pervious pavement in the low density area. The first solution presents the advantage of managing efficiently the costs whereas the second solution offers the opportunity to reduce the land takes for an equivalent water quality improvement. For these specific solutions, a land take reduction of 5,500 m^2 can be achieved for an equivalent cost of ~US$600k.

3. A further 2,000 m^2 to 2,400 m^2 are necessary to attenuate the 30 and the 100 year return periods respectively. In addition to the reduction in land take achievable based on the water quality benefits of source and site controls, a further land take reduction can be achieved by using SS to attenuate runoff to the required standards. Thus maximum reduction of land take for a TSS removal rate beyond 90% can be achieved by the use of a swale network or CBP and sub-surface storage.
4. Within an increase in costs and land take limited to 35% of those initially planned for the development of an end-of-pipe solution, significant water quality improvements can be achieved with a TSS removal beyond 85%. These solutions include the use of GRs and ITs.

Comparison of the cases where infiltration is prevented or encouraged.

By comparing these results with those presented in Bastien *et al.* (2010), where the same site was considered but infiltration was not permitted, it can be seen that:

- Infiltration of TP and TN at source level increase the overall removal for these pollutants reaching 95 and 93% removal for TP and TN respectively (in comparison with a maximum removal of 75 and 60% removal for TP and TN, respectively). This result is due to the removal processes associated with source and site controls, mostly based on the filtration process either by substrate or vegetation: these processes have a relatively low impact on the removal of TN and TP mostly found under dissolved forms (Taylor *et al.* 2005).
- Overall, the design of SuDS to prevent infiltration has very little impact on the overall cost (e.g. the lining of a swale to prevent infiltration only increases the whole life cost by 4%). As a result, the water quality and cost relationship are of a similar order of magnitude.

CONCLUSIONS

It can be concluded that a novel methodology has been presented which offers an opportunity for the key stakeholders involved in the drainage of surface runoff in urban areas to maximise the benefits of using SuDS in a treatment train. The reduction in regional land take can be achieved based on infiltration and/or attenuation of source and site controls. Despite the problems associated with offsetting regional land take with source and site controls, it has been shown that a different footprint for SuDS can be achieved by using SuDS in series rather than as an end-of-pipe control. The results obtained should be seen within the context of several SuDS related considerations which will vary greatly between catchments:

- land value in urban areas;
- increased amenity and biodiversity in urban areas;
- better management of accidental pollution; and
- infiltration rate related to site geology and impacting on SuDS design.

Further work will comprise investigating the potential value of SuDS source and site controls from the point of view of people living in close proximity. This will enable the definition of preferred treatment trains for urban areas depending on land use, catchment characteristics and stakeholders objectives.

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Optimising regional sustainable drainage systems pond performance using treatment trains

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ABSTRACT

The use of sustainable drainage systems (SuDS) or best management practice (BMP) is becoming increasingly common. However, rather than adopting the preferred "treatment train" implementation, many developments opt for end-of-pipe control ponds. This paper discusses the use of SuDS in series to form treatment trains and compares their potential performance and effectiveness with end-of-pipe solutions. Land use, site and catchment characteristics have been used alongside up-to-date guidance, Infoworks CS and the model for urban stormwater improvement conceptualisation to determine whole-life-costs, land take, water quality and water quantity for different SuDS combinations. The results presented show that the use of a treatment train allows approaches differing from the traditional use of single SuDS, either source or "end-of-pipe", to be proposed to treat and attenuate runoff. This outcome provides a more flexible solution where the footprint allocated to SuDS, costs and water quality can be managed differently to more comprehensively meet stakeholder objectives.

Keywords: Sustainable drainage systems (SuDS); Treatment train; Best management practice (BMP); Swale; Pond; Green roof; Permeable paving; Runoff quality

1. Introduction

The use of sustainable drainage systems (SuDS) or best management practice (BMP) has been made compulsory for virtually all new developments in Scotland. However, despite the design guidance [1], systems are often implemented using "end-of-pipe" or source controls SuDS rather than an integrated series of SuDS devices—a "treatment train". Indeed, in 2002, over 70% of sites in Scotland were reported as using only a single SuDS component [2].

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The management of runoff using a treatment train is preferred by the UK's environmental regulators as it provides the following advantages:

- Using different and complementary removal techniques can achieve enhanced pollutant performance;
- By making the drainage infrastructure visible, pollutant spills can be detected and managed in a more efficient manner;
- An enhanced level of treatment is achieved by treating pollutants closer to their source; and,
- The shock load effect on regional controls is reduced, thus enhancing biodiversity by providing a stable habitat.

Although these and other benefits of SuDS have been reported for some time, land take, construction costs, uncertainty regarding maintenance and adoption of SuDS are generally seen as barriers to implementation of source and site controls. In contrast, providing a good quality of life by improving environmental amenity and biodiversity in urban areas are key drivers for planners. By considering these views, the underlying philosophy of the presented research is that the development of a surface water management plan at an early stage, coupled with advances in how the treatment train is modelled, would help optimise water management and planning objectives. The aim of the reported study is therefore to develop a high value case study which may be used to evaluate the potential benefits of using different treatment train solutions for a case study. The case study allows the holistic evaluation of the different solutions undertaken by focusing on four key stakeholder objectives [3]:

- Land take;
- Whole life costs;
- Water quality; and,
- Managing flood risk.

Based on this analysis, the potential benefits achieved by the use of source and site controls may then be used as a basis for the objective reduction in regional treatment facility size, thereby offering the opportunity for developers and planners to manage the footprint differently whilst still satisfying water quality and quantity objectives.

2. Methodology

The methodology developed can be divided into three modules:

- Development of source, site and regional controls scenarios—this module focuses on selecting appropriate source and site controls that can be incorporated within the treatment train.
- Treatment train assessment based on key stakeholder objectives—this module aims to provide a novel holistic assessment of the treatment train. The key stakeholder objectives considered are:
- Land take: Determination of the land occupied by the SuDS devices is undertaken using recent design guidance [1,4].
- Costs: Whole life costs over a 50 year period.
- Water quality: To estimate the pollutant removal capacities of a range of SuDS, first order decay kinetics [5] will be used. This analysis will concentrate on the removal of total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP).
- Water quantity: Evaluation of the potential for source and site control to attenuate the volume reaching regional control.
- Proposal for regional control optimisation—this module discusses the possibility of reducing regional control size by objectively incorporating attenuation and water treatment at source and site control level.

2.1. Case study

The Clyde Gateway, situated along the River Clyde in Glasgow, is a priority regeneration area for the Scottish Government. Recent flooding in Glasgow, poor watercourse quality and the need to regenerate this neglected area as a "sought after" location led to the development of a forward looking surface water management plan [6]. The reported project uses a small part of the Clyde Gateway, Dalmarnock Road area (Fig. 1), to generate development scenarios. The Dalmarnock Road area, at the heart of the Clyde Gateway, is a former industrial area and due to this, infiltration of water into the soil will be prevented to avoid migration of pollutants into the groundwater. The study area comprises 20 hectares where a residential area encompassing 1500 houses will be constructed. If no source or site controls are used, a regional pond (RP) of approximately 2200 m^2 will be required to treat runoff to an acceptable level, and an additional 2600 m^2 will be required to store runoff up to a 100 year return period storm (2.5% of the catchment area).

Fig. 1. The Dalmarnock Road area contained within the Clyde Gateway boundaries.

Regarding current development plans for the Dalmarnock Road area, the northern extent of the site has been described as a "new destination and gateway" and will benefit from major public investment to improve public transportation [7]. Development density for the site suggests a decreasing density gradient from the north to the south: higher densities towards the city centre and decreasing progressively towards the suburbs. Although more detailed development plans will be considered in the future, the view adopted in presented research is that the development of SuDS will be dependent on land take and development density. Adopting this view, it has been considered that the SuDS implemented will vary in the amenity they provide depending on their location [8]:

- The northern part of the site will not see above ground SuDS devices unless they are part of the infrastructure (e.g., green roofs [GR]).
- The central part is more likely to adopt SuDS devices where they present a high amenity, thus improving biodiversity and urban well being (e.g., linear wetlands [LWs]).
- The southern part of the site will be developed at a low density, where the use of lower amenity SuDS is acceptable (e.g., swales [SW]).

The diffuse pollution arising from land use activities dispersed across the catchment mainly comprise suspended sediments, polycyclic aromatic hydrocarbons (PAHs), heavy metals, nutrients and phosphates issued from erosion, vehicles, maintenance of green spaces and animal droppings [9,10]. However, dissolved particles such as PAHs and heavy metals have an affinity for suspended particulate solids and are bound to them, mainly to the smallest particles [11]. Monitoring of pollutants generated by different land uses [12–14] has shown a certain consistency in the amount of pollutants that can be expected for different land uses. Within this context, the estimated pollutant concentrations for TSS, TN and TP can be found in Table 1. In most residential areas, roads are the main source of suspended solids and they are associated with major pollutants such as PAHs, oil and heavy metals.

Table 1
Expected pollutants concentrations for a residential development [15].

Residential development	Median	Coefficient of variation
TSS ($mg.l^{-1}$)	101.0	0.96
TP ($mg.l^{-1}$)	0.383	0.69
Total Kjeldahl Nitrogen ($mg.l^{-1}$)	1.900	0.73
Nitrite-N; Nitrate-N	0.736	0.83

2.2. Selection of potential SuDS techniques

Based on potential land use, site and catchment characteristics, the following seven key SuDS source, site and regional controls have been considered:

- LW or enhanced swale has been promoted within Glasgow as a method of reducing car use by providing a sustainable and safe green-blue link for pedestrians and cyclists.
- Provided infiltration is prevented, standard conveyance SW can be used in the southern part of the site where lower density development can be expected. Design is following CIRIA's recommendations [1].
- RP which discharges into the River Clyde is the "default end-of-pipe" solution in the southern part of the site. Design of the RP is based on recently published guidance [1,4] aimed at ensuring it captures the first flush for the whole area. The design can also include a volume dedicated to attenuate events up to the 100 year return period level.
- Extensive GR can be used instead of exposed roofs in the north part of the area where large roof surfaces are more likely to exist due to increased density. It should be noted that although the use of intensive GR, which offer a higher amenity, would achieve better attenuation (at a greater cost) they have not been considered in the reported research.
- Concrete block pavement (CBP) can be used where traffic speeds are below 60 km.h 1. As such, they can be used in very low density development and on a case-by-case basis in other areas. In this case, their use is concentrated in the areas of low density development.
- Water butts (WB) can be used in low density development to store and reuse water for gardening purposes.
- Subsurface storage (SS) can provide attenuation of runoff anywhere it is deployed in the study catchment.

The typical locations of these devices are illustrated in Fig. 2.

Logical combinations of the different SuDS devices allow consideration of 23 different treatment trains comprising one to six SuDS that can be assessed for water quality performance and three SuDS that can be assessed on their ability to attenuate runoff.

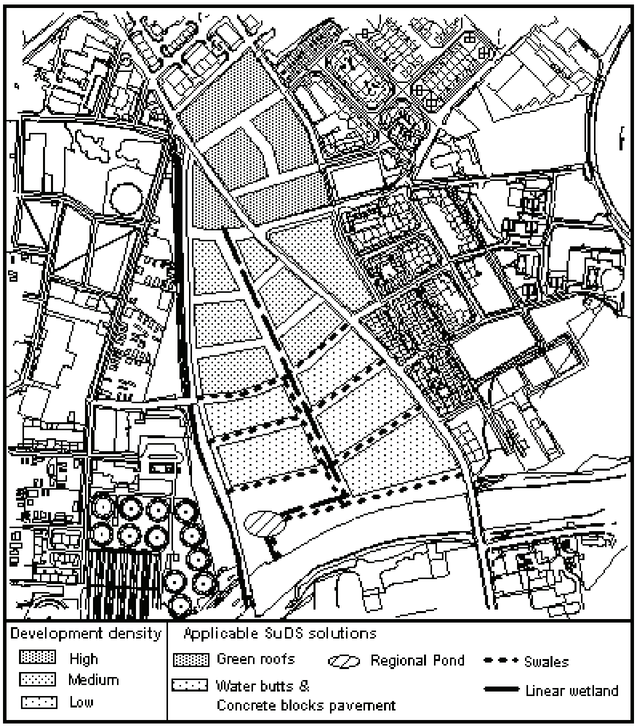

Fig. 2. SuDS deployment.

2.3. Treatment train assessment

To support the methodology, water quality modelling tools and costs identified from the literature are used.

2.3.1. Model for urban stormwater improvement conceptualisation

The model for urban stormwater improvement conceptualisation (MUSIC) developed by eWater Cooperative Research Centre is a hydrological model coupled with a water quality model. The hydrological and water quality performances of the different SuDS are modelled by a series of well mixed water bodies and using first order kinetics observed in SuDS monitoring studies [16]. Where sedimentation is the main removal mechanism, theoretical removal rates based on sedimentation equations are determined. When other removal mechanisms (e.g., biological or filtration) dominate or compete with sedimentation, the pollutant removal is considered as a unique process and rates are determined based on calibration surveys. For the SuDS considered in this case study, theoretical calculations derived from sedimentation equations and calibration surveys for the different treatment devices have allowed a range of values for k and C* to be determined [17]. It should be noted that the calibration of k and C* relies heavily on the particle size distribution of the sediment. Despite much of the work in this field being site specific, a review undertaken by Walker et al. [18] indicated a certain consistency regarding the particle size distribution at different sites. In the absence of site specific data for the Glasgow area, it was therefore considered acceptable to adopt particle size distribution data from surrogate catchments.

The MUSIC model has been used due to its ability to model a wide range of SuDS devices. The MUSIC model is used to estimate water quality improvements for SuDS where surface areas of facilities are considered as an important factor in the removal of pollutants (ponds, SW and LW). To estimate water quality benefits of the treatment train for the case study, one year return period rainfall event of 60 minutes duration (M1-60) corresponding to 12 mm of rainfall associated with event mean concentrations determined by Duncan have been used [12]. It is expected that both the chosen rainfall event and the associated concentrations will represent standard conditions for which SuDS have been designed.

2.3.2. Whole life cost estimation

For all the SuDS and infrastructures considered, the costs have been determined based on the construction costs of the devices and associated maintenance over a 50 year period (Table 2). As these systems have been chosen to provide a high amenity to the community and support urban biodiversity, a high level of maintenance has been used to determine the costs. The net present value of costs has been calculated by adjusting future costs with a discount rate of 3.5% up to 30 years, followed by 3% for the remaining years [19].

3. Results and discussion

3.1. Preliminary results

Based on the data determined for each SuDS device, assessment of the different treatment trains on the aspects of water quality, land take and costs is illustrated in Fig. 3a, Fig. 3b and Fig 3c. It should be noted that, at this stage, each SuDS device and treatment train has been designed to maximise pollutant removal.

As illustrated, by using SuDS in series, significant benefits in terms of water quality can be achieved. From a basic removal of 68% of TSS for a single RP, the removal can reach more than 90% when several SuDS in series are used. By increasing the removal of TSS, the removal of small particles is improved, thus improving the treatment for heavy metals and PAHs as these pollutants are more likely to be bound to the small particle size fraction of TSS [11]. Although the improvement in water quality is

Table 2
Maintenance activities and associated costs for the SuDS devices considered [4,19–426]

	Capital cost (k£)	Maintenance activities	Frequency (months)	Maintenance activities	Frequency (months)	Maintenance costs (k£) [1]	Present value (k£)
SuDS [reference]							
Regional pond [21]	27.7	Inspection, reporting and info management	1	Sediment removal from engineered silt trap	6	192	220.0
		Litter and minor debris removal	1	Sediment removal from forebay	36		
		Grass cutting	4	Sediment removal from the pond	120		
		Barrier vegetation pruning	36	Vegetation replacement	300		
		Barrier vegetation weeding	12	Removal and disposal of construction sediments	Once after 12 months		
		Aquatic vegetation management	12				
		Algae removal	4				
Swale [21]	50.1	Inspection, reporting and info management	1	Vegetation replacement	300	106	156.1
		Litter and minor debris removal	1	Removal and disposal of construction sediments	Once after 12 months	143	202.6
Linear wetland [21]	59.6	Grass cutting	1				
		Sediment removal	120				
Sub-surface storage [22]	124.6*V[2] + 14614	Grass cutting	1.5	Controlled disposal/Haulage of silt	120	0.375*V[2] + 2780	—
		Litter removal	1.5	Remove blockages	120		
		Inspection of structures	6	Jetting	120		
		Desilt inlets and outlets	12	Repair broken components	120		
Concrete block pavement [20,21]	2782.5	Inspection, reporting and info management	1	Remove block paves and stockpile to be washed	300	792	3574.0
		Litter and minor debris removal	1.5	Install replacement geotextile, install new 5 mm single aggregate bedding layer and reinstate block	300		
		Permeable pavement sweeping	4				
Water butts [23]	61.0	—	—	—	—	0.0	61.0
Green roofs [24]	1048.2	Inspection of drainage system	6	Water and weed of the turf/replacement if necessary	0.5	463	1511.5
		Replacement of water proofing membrane	480				
Infrastructures							
Exposed roofs [24]	574.5	Inspection of drainage system	6	Replacement of water proofing membrane	120	1144	1718.6
Asphalt pavement [25]	1961.7	Inspection of drainage system	120	Surface dressing	Once after 120 months, then every 60 months	925.3	2887.0
		Surface course replacement	240				
		Surface course repairs in 6% of the surface	240				
		Excavation and full reinstatement on 0.5% of the surface	240				
Pipe network [4,26] [3]	—	—	—	—	—	—	—

[1] Maintenance over 50 years [19]
[2] Stored volume (m3)
[3] Calculated in function of pipe length, diameter, material, depth and manholes following Scottish Water requirements [4]

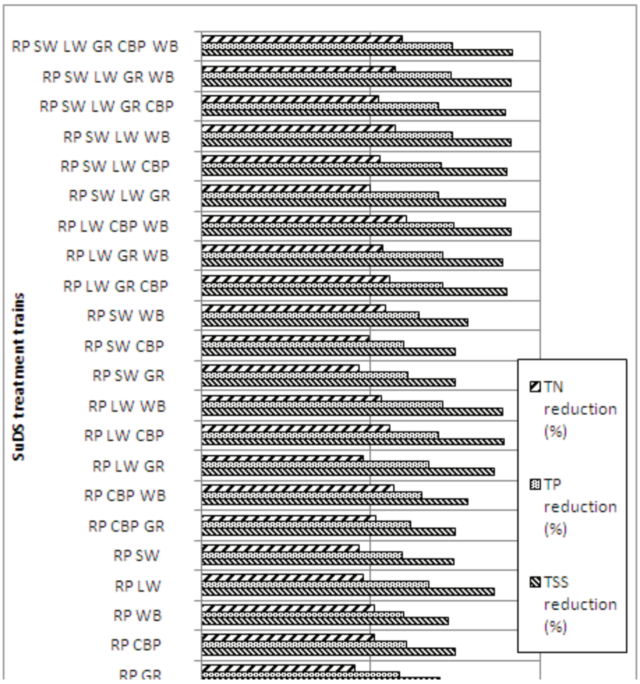

Fig. 3a. Water quality estimation for the different catchment wide SuDS treatment trains.

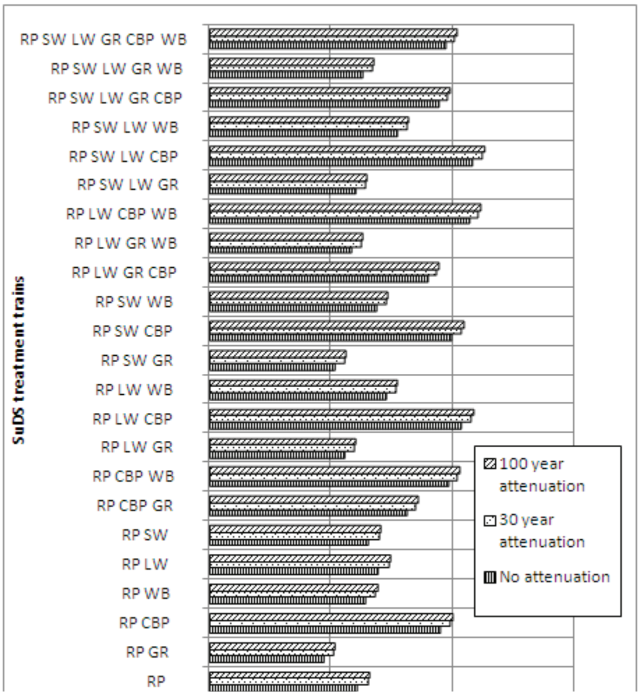

Fig. 3c. Whole life costs for the different catchment wide SuDS treatment trains.

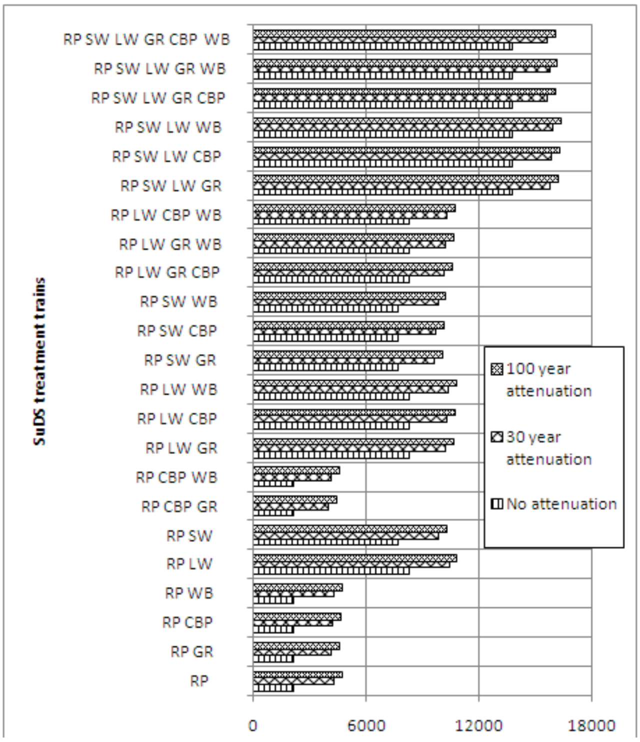

Fig. 3b. Land take estimation for the different catchment wide SuDS treatment trains.

desirable, the whole life costs associated with the different treatment trains show that using multiple SuDS source and site controls has a significant cost impact and in this case can multiply the cost of the initial project by up to five times. However, it should be noted that the implementation of some devices, although initially expensive, yields significant benefits. In particular, GR appear to be beneficial in the long term. This view, supported by several authors [27,28], is based on the theoretical assumption that the choice of a low maintenance vegetation associated with an extended lifespan can offset the construction and maintenance of an exposed roof. The longer term benefits may be reinforced by evaluating the extent to which GR provide better insulation and reduce heating and cooling costs as a result [24,27]. Similarly, the implementation of SW in the low density area does not add a significant cost to the project and they can easily be incorporated in roadside verges.

A further point to note is that unless SuDS are part of the infrastructure (e.g., CBP or GR), they add significant land take to that of the initial regional control. The attenuation of different return periods also adds significant land take despite the opportunity to size some source and site SuDS to attenuate up to 30 year return period events.

Overall this section confirms the main stakeholder fears (e.g., whole life costs and land take) regarding the use of SuDS treatment trains rather than using only single regional SuDS. Indeed, this initial analysis has shown that despite an improved treatment of up to 20%, 19% and 15% for respectively TSS, TP and TN, some treatment trains add significant land take and/or costs to the project.

3.2. Proposition to reduce regional control size

In new developments there is often pressure to reduce the size of a RP. Logic would suggest that a reduction in land take can be achieved by optimising the design of the upstream treatment train. Within this context, regional control size can be reduced by two different means:

- Reduction of the treatment volume by taking into account benefits of source and site controls.
- Reduction of the attenuation volume by providing attenuation at source and site control levels.

3.2.1. Reduction of treat ment volume

Pond performance is largely driven by pond surface area [29]. Consequently, reducing pond surface area will reduce pollutant removal by increasing the hydraulic loading. As shown in Fig. 3, the use of a single pond achieves a theoretical 68% removal of suspended solids. If this performance is considered adequate, then if the treatment train produces a level of treatment beyond that level, it follows that the RP may be reduced in size until the target performance is reached. Table 3 illustrates the land take of source, site and regional controls achieving at least a reduction of 68% of TSS. For some treatment trains, the regional control appears to be unnecessary because the upstream treatment train achieves a removal of suspended solids beyond 68%. However, this solution may not be acceptable for two reasons:

- The pond is the last control before the runoff is discharged and it could be considered as security in case source and site controls do not perform to the required standards.
- More importantly, it should be noted that if better treatment and degradation could be achieved upstream for suspended solids (and bound pollutants such as heavy metal and PAH's), the reduction of treatment volume reduces the opportunity to degrade dissolved pollutants [30].

As illustrated in Table 3, in most cases, the reduction in land take of the regional control does not compensate for the land used by upstream source and site controls unless these are part of the infrastructure (e.g., CBP). Although this may be viewed as a disadvantage, it may be considered by the developer as an alternative way to

Table 3
Achievable reduction in land take for regional control based on 68% TSS removal.

SuDS treatment trains with CBP, GR, LW, RP, SW, WB	Initial treatment train land take (m^2)	Achievable reduction of regional SuDS land take (m^2)	Achievable reduction of regional SuDS land take (%)	Achievable reduction of SuDS treatment train's land take (%)
RP	2200	0	0	0
RP GR	2200	0	0	0
RP CBP	2200	433	20	20
RP WB	2200	288	13	13
RP LW	8300	2200	100	27
RP SW	7724	433	20	6
RP CBP GR	2200	433	20	20
RP CBP WB	2200	719	33	33
RP LW GR	8300	2200	100	27
RP LW CBP	8300	2200	100	27
RP LW WB	8300	2200	100	27
RP SW GR	7724	433	20	6
RP SW CBP	7724	433	20	6
RP SW WB	7724	571	26	7
RP LW GR CBP	8300	2200	100	27
RP LW GR WB	8300	2200	100	27
RP LW CBP WB	8300	2200	100	27
RP SW LW GR	13824	2200	100	16
RP SW LW CBP	13824	2200	100	16
RP SW LW WB	13824	2200	100	16
RP SW LW GR CBP	13824	2200	100	16
RP SW LW GR WB	13824	2200	100	16
RP SW LW GR CBP WB	13824	2200	100	16

spatially manage the SuDS footprint. An example of this is the land take associated with SW: their position along the roads may make them more acceptable than setting aside a large area for a RP.

3.2.2. Reduction of the attenuation volume

The attenuation of the runoff volume can be undertaken at source and site control levels. The land take associated with the storage of the 1, 30 and 100 year return period events in addition to the land take of the permanent pool is respectively of 3529, 4363 and 4788 m2 for respective volumes of 2616, 5560 and 7220 m3. Reduction of volumes reaching the regional control through the use of source and site control will help reduce land occupied by the regional control. Within this context, the SuDS can either be designed as specific attenuation devices or to simply slow the runoff.

Regarding SuDS slowing the runoff:

- Swales and LWs: Infoworks simulations have indicated that the equivalent reduction volume achieved is less than 15% for the LW and less than 0.5% for the SW for 100 year return period events.
- Regarding SuDS designed specifically for attenuation:
- CBP: The sub-grade is designed to store up to a 30 year return period event.
- WB: these are designed to store 0.3 m3 per dwelling.
- GR: Literature on the performance of GR in terms of attenuation reports a wide range of values depending mostly on the depth of substrate [1]. Deutsch et al. [31] recommend assuming the retention of the first 25 mm of each rainfall event. This value is associated with the costs determined by Wong et al. [24] for the development of an extensive green roof and takes into account potential economies realised on the construction of a conventional roof to determine the whole life cost as a function of the stored volume.
- RPs: Retention of water takes place at the RP level to attenuate runoff for the whole area runoff.
- SS can store the designed volume and impacts only on costs.
- Based on the costs estimates detailed previously (Table 2) and the expected performances, the whole life costs as a function of the stored volume have been estimated for each SuDS device. The associated whole life costs (Table 4) for each SuDS has been calculated:
- As an additional cost for SuDS initially designed for water quality when additional costs due to storage could be dissociated from the costs associated with water quality benefits (e.g., pond).

Table 4
Equations with WLC: Whole life costs (£); V: Stored volume (m^3) ; Vmax: Maximum volume stored (m^3).

	Equation	References
RP	WLC=13.41*V+16284	[21]
WB	WLC=571.7*V; Vmax+106.5	[23]
GR	WLC=318.6*V+9.197; Vmax+650	[24]
SS	WLC=133.3*V+21349	[22]
CBP	WLC=179.5*V+98998	[21,25]

- As a supplementary cost when water quality and water quantity benefits are not dissociable (e.g., concrete blocks pavement and GR).
- As a supplementary cost for SuDS only designed for water attenuation (SS).

The whole life costs calculated take into account the potential economies realised on infrastructure (e.g., exposed roofs coverings).

In summary, the use of SW and LWs can be considered as cost efficient when designing for water quality alone. However, where attenuation is also considered, the benefits are less attractive. WB are the most expensive solutions and are limited to the attenuation of small rainfall events. The use of GR appears to be the most cost effective solution to store runoff, but they offer only a limited storage volume. Thus, when compared to traditional SS, integrating the attenuation storage within the existing retention pond is the most cost effective solution to store high return period events. However, where land take is an issue, SS will remain attractive.

Overall, the choice of SuDS devices to attenuate runoff will depend on the design return period. Low return period events can be attenuated using source and site controls designed to store frequent rainfall events. Whereas attenuation of high return period (>30 years) will require dedicated structures which require additional land take or costs to the project.

3.3. Cost, land take and water quality performance relationships

Based on the results outlined thus far, it is possible to consider how different attenuation and water quality improvement levels impact on both cost and land take. This is best done by considering three design scenarios:

- Where the design is for water quality improvement only.
- Where the design is for water quality improvement and limited retention.
- Where the design is for water quality improvement and robust retention.

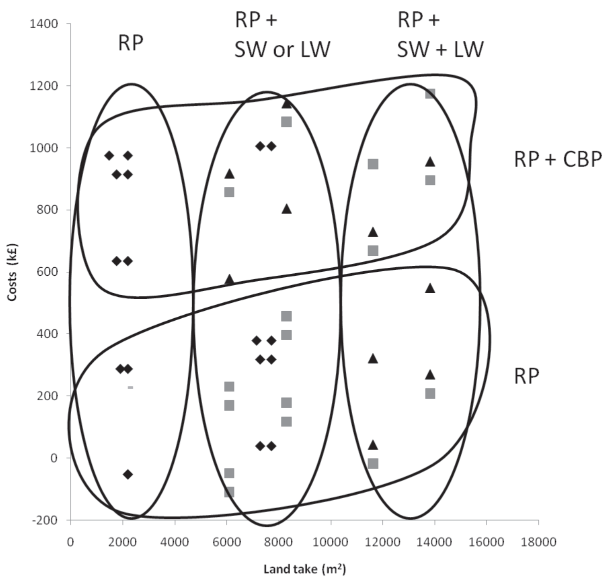

Fig. 4a. Cost size attenuation relationship when no attenuation is required.

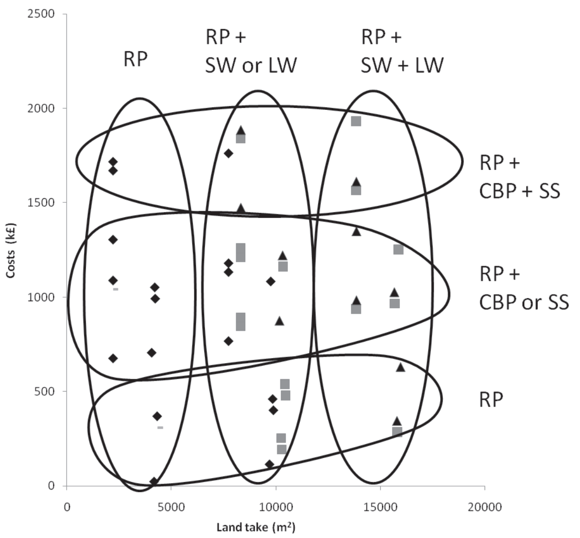

Fig. 4b. Cost size attenuation relationship with 30 years attenuation.

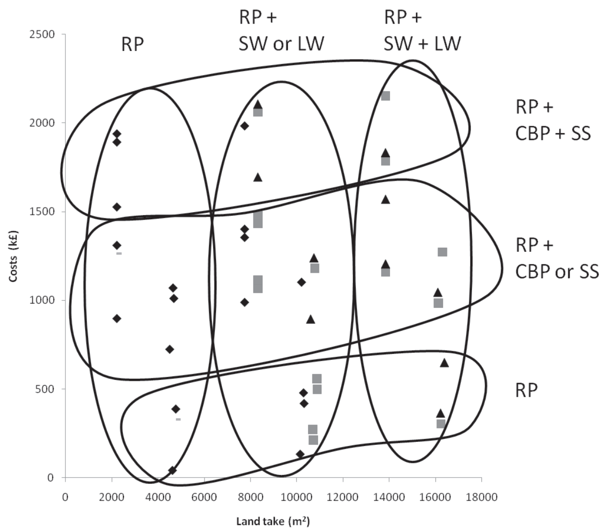

Fig. 4c. Costs size attenuation relationship with 100 years attenuation.

Data for these three scenarios are presented in Fig. 3 where relationship between land take, costs, water quality and water quantity are illustrated.

Considering the Fig. 4a, significant water quality improvements can be obtained compared to the initial solution of using an end-of-pipe pond: the initial removal rate, below 70% for TSS can be improved beyond 90% by either:

- Implementing a swale network and a LW; or,
- By using pervious pavement in the low density area in conjunction with the implementation of the swale network or the LW.

The first solution presents the advantage of managing efficiently the costs whereas the second solution offers the opportunity to reduce the land takes for an equivalent water quality improvement. For these specific solutions, a land take reduction of 5500 m^2 can be achieved for an equivalent cost of ~£250 k.

A further 2000 m2 to 2400 m2 are necessary to attenuate the 30 and the 100 year return periods respectively (Fig 4b and Fig 4c). In addition to the reduction in land take achievable based on water quality benefits of source and site controls, a further land take reduction can be achieved by using SS to attenuate water quantity to the required standards. Thus maximum reduction of land take for a TSS removal rate beyond 90% can be achieved by the use of a swale network or a LW in association with CBP and SS. The costs appear to be mainly driven by the use of SS and concrete block paving in addition to the use of a regional control pond. Whereas land take is driven by the use of SW and LWs. GR and WB have a relatively limited impact in comparison to the use of other SuDS.

These plots can serve as a basis for discussion between all the stakeholders involved in the drainage of the Dalmarnock Road area.

4. Conclusions

A novel methodology is presented which offers an opportunity for the key stakeholders involved in the drainage of surface runoff in urban areas to maximize the benefits of using SuDS in a treatment train. The reduction in regional land take can be achieved based on water quality performance or source and site control attenuation. Despite the problems associated with off-setting regional land take with source and site controls, it has been shown that a different footprint for SuDS can be achieved by using SuDS in series rather than as an end-of-pipe control. The results obtained should be seen in the context of several SuDS related considerations which will vary greatly between catchments:

- Land value in urban areas;
- Increased amenity and biodiversity in urban areas;
- Better management of accidental pollution; and
- Improved pollutants degradation.

Further work will comprise investigating the potential value of SuDS source and site controls from the point of view of people living in close proximity. This will enable the definition of preferred treatment trains for urban areas depending on land use, catchment characteristics and stakeholders objectives.

Acknowledgment

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